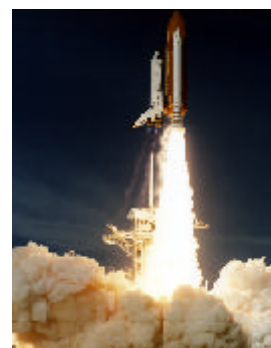
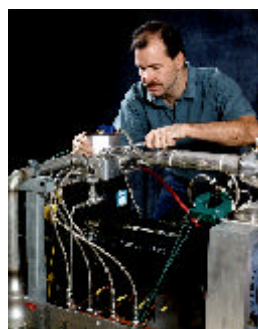


IEA Agreement on the Production and Utilization of Hydrogen



Annual Report 1996

Edited by
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1996 Annual Report: IEA Agreement on the Production and Utilization of Hydrogen

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HYDROGEN

INTRODUCTION

Hydrogen is the simplest, naturally occurring element that can be found in numerous materials, such as natural gas, coal, biomass, and water. Recent years have seen an increasing interest in hydrogen technologies as a result of the growing awareness of environmental threats to which hydrogen produced by solar-generated electricity appears to be the near-perfect solution. As an energy carrier, it is anticipated to join electricity as the foundation for a globally sustainable energy system using renewable energy. This virtually non-polluting, flexible fuel has many potential uses.

One of the most visible uses of hydrogen today has been in the space industry, namely to propel the space shuttle and to provide all of the shuttles' electrical power through on-board fuel cells. In the next century, many vehicles and aircraft are likely to be powered by hydrogen, in liquid, slush, or gaseous form. Hydrogen will also be a clean source of electricity for lighting, heating, and cooling of buildings.

HYDROGEN PRODUCTION

The most utilized practice for producing hydrogen today is steam reforming of natural gas. However, for applications requiring pure hydrogen, the relatively expensive technique of electrolysis (the use of an electric current to dissociate, or split, water into its hydrogen and oxygen components) is used. In order to realize a hydrogen energy future, advanced technologies must be developed to produce hydrogen from sustainable resources, at costs competitive with fossil fuels. The most promising technologies under investigation fall into three general process categories: photobiological, photoelectrochemical, and thermochemical. Photobiological and photoelectrochemical systems utilize sunlight to split water; while thermochemical systems, including gasification and pyrolysis systems, use heat to produce hydrogen from sources such as biomass and solid waste.

Photobiological

Most photobiological systems use bacteria and green algae to produce hydrogen. These systems hold great promise for long term sustainable hydrogen production, but face two major barriers for meeting the cost limitations. These barriers are the fairly low solar conversion efficiencies of these systems of around 5-6%, and the fact that nearly all enzymes that evolve hydrogen from water are inhibited in their hydrogen production by the presence of oxygen. Research efforts are focusing on overcoming this oxygen intolerance by developing strains of the green algae, *Chlamydomonas*, which contain oxygen-evolving enzymes, and thus can produce oxygen and hydrogen simultaneously. Genetic alterations of *Chlamydomonas* are being investigated in attempts to improve the solar conversion efficiencies. These new genetic forms are predicted to reach efficiencies on the order of 10%.

Photoelectrochemical

Photoelectrochemical production uses semiconductor technology in a one-step process of splitting water directly upon sunlight illumination by combining a photovoltaic cell and electrolysis into a single device. Research efforts are being focused on identifying structures and materials which will meet the high voltage requirements to dissociate water, not be susceptible to the corrosiveness of the aqueous electrolytes used in the electrolytic process, and are cost-effective. Amorphous silicon devices are one of the types most favored, due to their lower cost. These photovoltaic devices have achieved

efficiencies of 7-8%. Photovoltaic devices, using more expensive materials, have demonstrated efficiencies of up to 13%. Researchers are now working to combine the low cost materials and high conversion efficiency materials to achieve a practical application of this promising technology.

Thermochemical

Gasification and pyrolysis methods can be used to convert biomass or municipal solid waste into a vapor which can then be steam reformed to recover the hydrogen. For pyrolysis, a fast-pyrolysis reactor can be directly coupled to a steam reformer. To date, yields of 12-17% hydrogen by weight of dry biomass have been achieved. Gasification of municipal solid waste has shown equally promising results. Both of these thermochemical processes have the potential to be one of the lowest-cost production methods for hydrogen. Efforts are now being placed on identifying optimum reforming catalysts.

HYDROGEN UTILIZATION

Today's research and development efforts for hydrogen utilization are focused on those technologies which will facilitate the progression to a hydrogen energy economy. These technologies include fuel cells, internal combustion engines, and hydrogen burners.

Fuel Cells

There are several types of fuel cells, depending on the nature of the electrolyte used. The most mature technology for near-term use in large vehicles is the phosphoric acid fuel cell (PAFC). PAFCs are already being commercialized for stationary power applications and for demonstrations in larger fleet vehicles, such as buses.

Because the power density of the PAFC is too low and the start-up time is too long for use in automobiles, the proton-exchange membrane (PEM) fuel cell is the prime mid-term candidate for automotive applications. The PEM is able to operate at fairly low temperatures (around 80°C) and can start up from ambient temperature at partial load. These characteristics, combined with the higher power density, make the PEM more adaptable for automobile use than the PAFC.

For longer term, primarily in the utility sector, solid oxide fuel cells (SOFC) are being developed. The SOFC design has fewer components and ultimately may require less maintenance. Thus, in the long run, they may be less expensive than other fuel cell types.

Internal Combustion Engines

Hydrogen use in an internal combustion engine (ICE) was demonstrated over 100 years ago. The hydrogen-fueled ICE offers the potential of no carbon and very low nitrogen oxide emissions, combined with high thermal efficiencies. Research and development efforts of recent years have been focused on solving some of the key inhibitors to the ICE becoming cost effective, namely problems related to engine combustion, fuel delivery, and practical storage.

Burners

Hydrogen burners can be used to generate electricity for utilities and provide heat to industry and homes. Because the burning of any fuel in air results in the production of nitrogen oxide emissions, research efforts have been focused on optimizing hydrogen combustion to eliminate these emissions. A number of routes are being investigated including: cost-effective methods for eliminating nitrogen

from the fuel mixture, reducing the peak combustion temperature and time spent at the peak temperature, and the study of the combustion fluid dynamics required to completely oxidize hydrocarbons and hydrogen fuels.

HYDROGEN TRANSPORTATION AND STORAGE

The future of hydrogen will require the creation of a distribution infrastructure of safe and cost-effective transport and storage. Present storage methods are too expensive and do not meet the performance requirements of future applications. Transport methods will need to be developed based on the production and storage systems that come into use as the hydrogen energy economy evolves. Utilization methods will require different types of storage technologies. While energy efficiencies and system cost are the most important factors when considering stationary storage for utility applications, weight and size are predominant for mobile applications. Thus, research efforts are focused on developing physical and solid-state storage systems that will meet the diverse future application demands.

Physical Storage

Technologies for stationary storage are commercially available today and are in use in industrial applications for both compressed gas or cryogenic liquid. Mature-stage research for these technologies is focused on fine-tuning to maximum energy content per unit of volume or weight of these hydrogen storage systems. However, these technologies are currently impractical for providing hydrogen for mobile technologies, since the size of the tank required to supply a range comparable to a gasoline-powered vehicle would be too large and too heavy to be cost-effective. This is primarily due to the pressure limitations of 14 to 17 megapascals (MPa) for the current technologies. Thus, research is focusing on developing new graphite composite materials which may be able to store hydrogen at pressures as high as 41 MPa.

Solid-State Storage

A number of solid-state methods are being investigated as a means of improving the safety and efficiency of hydrogen storage over the current methods of gas or liquid hydrogen storage for longer-term hydrogen applications. The most promising methods include metal hydrides, gas-on-solids adsorption, and glass microspheres.

Metal Hydrides - Metal hydrides have excellent potential for hydrogen storage due to their high volumetric density, safety, and ability to deliver pure hydrogen at a constant pressure. There are more than 80 metals in existence that form metal hydrides by absorbing and retaining hydrogen under certain temperature and pressure conditions. The high volumetric densities of hydrides combined with their safety characteristics make them very suitable for stationary storage. However, they are constrained with regard to mobile applications due to their low gravimetric densities, expressed as hydrogen as a percent of total hydride weight. As a result, efforts are being focused on developing materials with higher gravimetric densities that can operate under conditions consistent with mobile storage. Some of the more promising technologies are improved metal alloys, high-efficiency metal hydrides, and nonclassical metal hydride complexes.

Gas-On-Solids Adsorption - The ability of high-surface-area, chemically-activated carbons to retain hydrogen on their surfaces is well known. However, relatively high pressures and extremely cold temperatures are required. These materials are also limited by relatively low volumetric and gravimetric densities, as well as the overall cost of the process.

Carbon nanotubes and carbon aerogels are two technologies that may have the potential to become more practical and cost-effective in the long-term for hydrogen storage. For carbon nanotubes, hydrogen attaches to the carbon surface and also fills the micropores, allowing hydrogen gas to condense into a liquid state at relatively high temperatures. Preliminary results on nanotubes show storage capacities of 8.4 weight percent hydrogen at 82 K and 0.07 MPa. Research is now focusing on improving the amount of hydrogen which can be stored at near-ambient temperatures.

Similarly, carbon aerogels have shown a great deal of promise for improved storage capacities. Adsorptions of 3.7 weight percent at 8.3 MPa have resulted from laboratory tests. Work is now focusing on optimizing the aerogel structure in order to maximize hydrogen adsorption over a wide range of temperatures and pressures.

Glass Microspheres - Glass microsphere technology is also under investigation, where at temperatures of 200-400 °C the increased permeability of the glass permits the spheres to be filled by hydrogen under pressure through immersion in high-pressure hydrogen gas. Once the glass is cooled to ambient temperatures, it is no longer permeable and the hydrogen is trapped; subsequent raising of the temperature will release the hydrogen. These microspheres have the potential to be less costly to produce and safer than conventional gas or cryogenic liquid containers.

TECHNOLOGY BARRIERS

Cost remains the largest single obstacle for hydrogen technologies, although a number of engineering challenges exist as well. The world's infrastructure is not yet geared to a hydrogen-based economy. This combined with the higher costs of hydrogen over existing fuels, will likely keep hydrogen usage restricted to smaller, niche markets in the near- to mid-term, with a sustainable hydrogen future being a long-term goal.

OVERVIEW OF THE HYDROGEN IMPLEMENTING AGREEMENT

THE INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA) was established in 1974, following the first oil crisis and is managed within the framework of the Organization for Economic Cooperation and Development (OECD). The mission of the IEA is to facilitate collaborations for the economic development, energy security, environmental protection and well-being of its members and of the world as a whole. The IEA is currently comprised of 23 member countries, 13 of which are active participants in the program focused on the Utilization and Production of Hydrogen.

The Hydrogen Program, or Implementing Agreement, has been in existence for nearly 20 years. Its mission is to advance hydrogen technologies and accelerate hydrogen's acceptance and widespread utilization. Past collaborations have been in the areas of Thermochemical Production, High Temperature Reactors, Electrolysis, Storage, Safety, and Markets.

GUIDING PRINCIPLES OF THE HYDROGEN AGREEMENT

The members of the IEA Hydrogen Program agree that hydrogen technologies offer many advantages and, thus, merit serious attention. The following are the guiding principles on which the scope of the Agreement is based:

- Hydrogen--now used as a chemical for up-grading energy carriers--will in the future increasingly become an energy carrier itself. It is necessary to carry out the analysis, studies, and research which will ultimately lead to a significant role for hydrogen in the future.
- Hydrogen is seen to have the potential for short, medium and long-term applications and the steps to realize the potential for applications in appropriate time frames must be understood and implemented.
- Hydrogen can be produced as a storable, clean fuel from the world's sustainable non-fossil primary energy sources - solar energy, wind energy, hydropower, biomass, geothermal, nuclear fission, tidal, and eventually nuclear fusion. It can be used as a fuel for a wide variety of end-use applications including important uses in the transportation and utility sectors.
- All countries possess sustainable primary sources; hence, hydrogen energy technology offers an important potential alternative to fossil fuel energy supply (in many instances to imported fuels). Utilization of hydrogen technology can contribute to energy security, diversity and flexibility.
- All sustainable energy sources require conversion from their original form. Conversion to electricity and/or hydrogen will constitute two prominent options in the future.
- Hydrogen can assist in the development of renewable and sustainable energy sources by providing an effective means of storage, distribution and conversion; moreover, hydrogen can broaden the role of renewables in the supply of clean fuels for transportation and heating.
- Barriers, both technical and non-technical, to the introduction of hydrogen are being reduced through advances in renewables and hydrogen systems including progress in addressing hydrogen storage and safety concerns.
- Hydrogen is used for the improvement and efficiency of fossil fuels produced from heavy oil and

coal, and to interconvert gaseous, solid and liquid fuels. The use of hydrogen in such applications reduces harmful emissions. Ultimately, with the addition of hydrogen, carbon dioxide emissions can be used to produce useful chemicals and fuels.

- Significant use of hydrogen will contribute to the reduction of energy-linked environmental problems.
- Hydrogen energy systems have potential value for locations where a conventional energy supply infrastructure does not exist. The development of hydrogen technology in niche applications will result in improvements and cost reductions which will lead to broader application in the future.

The members recognize that a long-term research and development effort is required to realize the significant technological potential of hydrogen energy. This effort can help create competitive hydrogen energy production and end-use technologies and support development of the infrastructure required for its use.

If this is realized, it will contribute to the sustainable growth of the world economy by helping to ensure a stable supply of energy and by helping to reduce future emissions of carbon dioxide. Cooperative efforts among nations can help speed effective progress towards these goals. And inasmuch as hydrogen is in a pre-commercial phase, it is particularly suited to collaboration as there are fewer proprietary issues than in many energy technologies.

MISSION/PURPOSE

The mission of the IEA Hydrogen Program is to advance hydrogen technology and accelerate its acceptance and widespread utilization in member countries of the IEA and others through a program of collaborative research activities and studies.

GOALS/OBJECTIVES

- To carry out effective, high priority collaborative projects which address important technical problems facing hydrogen technology.
- To address common research needs of the member countries.
- To establish projects which are appropriate to international collaboration.
- To promote the acceptance of hydrogen technology and reduce negative perceptions.
- To address market barriers which could impede the widespread and cost-effective utilization of hydrogen technology.
- To increase the knowledge and information available on hydrogen technology and provide analysis for energy policy-makers in IEA member countries concerning the development and future potential of hydrogen technology.
- To meet the needs of end-users and help accelerate the commercialization of hydrogen technology.

STRATEGIES TO ACHIEVE THE GOALS

- Transform the Hydrogen Executive Committee into a proactive body which undertakes the identification, selection, and management of high priority projects and coordinates an intensified program of cooperative work.

- Rank hydrogen technologies and applications by priority and identify those which would benefit from the support of international collaborative research.
- Collaborate on discrete tasks, which are related to those identified technologies and applications consistent with Participants' national objectives.
- Utilize careful planning and management to ensure the production of useful results, both in terms of technical advances as well as with respect to return on investment, in order to attract increased national participation, to demonstrate the advantage of multilateral cooperation, and to benefit the national programs of member countries.
- Develop effective evaluation mechanisms to assure the quality of projects and to enhance the impact of their results.
- Utilize, in general, the mechanism of task-sharing to perform the joint activities. However, cost-shared activities may be considered on a case-by-case basis.
- Establish effective management and reporting procedures for projects and the overall program.
- Obtain industry input into basic research and market-oriented R, D & D activities to increase the usefulness of the research results and probability of their adoption and utilization.
- Undertake projects to develop the hardware, designs, design tools, and information needed to reduce the cost and technical risk of hydrogen technologies and their application.
- Provide the scientific and technical basis for internationally approved standards for hydrogen technologies and their application.
- Produce reports on hydrogen technology subjects which will be used to disseminate information of various types which can be of value to researchers in the hydrogen energy field and to decision makers. It must be insured that the information is provided in the appropriate depth and form for the intended audience.

SCOPE OF THE COLLABORATIVE RESEARCH PROGRAM

The scope of the collaborative efforts of this Program will be innovative hydrogen technologies and approaches relating to hydrogen production (especially renewable energy-based), transportation, conversion, storage, and utilization. Total system designs including safety and environmental considerations will be an important element. Excluded from the scope of this Program are fuel cell development and use in electric cars although such activities will be monitored as they relate to the development and future potential of hydrogen technology.

Coordination will be maintained with IEA Agreements having related elements, including Fuel Cells, SolarPACES, and Greenhouse Gases R & D Agreements and others, as appropriate, to avoid duplication of effort and to share information of mutual interest.

CURRENT ACTIVITIES

At its March 1993 meeting, the Executive Committee of the Hydrogen Agreement selected three priority topics for collaboration, identified lead countries, and initiated the planning of the following new Tasks:

- Task 10: Photoproduction of Hydrogen
(Operating Agent: Norway)
- Task 11: Integrated Systems
(Operating Agent: United States)
- Task 12: Metal Hydrides for Hydrogen Storage
(Operating Agent: United States)

During 1995, Programmes of Work were developed and approved for all three of the tasks.

The signatories to the Hydrogen Implementing Agreement for 1996 were as follows:

Canada
European Commission
Germany
Italy
Japan
Netherlands
Norway
Spain
Sweden
Switzerland
Turkey
United Kingdom
United States

The IEA Hydrogen annexes and their duration are summarized in the following table:

Current and Completed Annexes of the IEA Hydrogen Implementing Agreement

Annex 1	Thermochemical Production	1977-88
Annex 2	High Temperature Reactors	1977-79
Annex 3	Assessment of Potential Future Markets	1977-80
Annex 4	Electrolytic Production	1979-88
Annex 5	Solid Oxide Water Electrolysis	1979-83
Annex 6	Photocatalytic Water Electrolysis	1979-88
Annex 7	Storage, Conversion and Safety	1983-92
Annex 8	Technical and Economic Assessment of Hydrogen	1986-90
Annex 9	Hydrogen Production	1988-93
Annex 10	Photoproduction of Hydrogen	1995-
Annex 11	Integrated Systems	1995-
Annex 12	Metal Hydrides for Hydrogen Storage	1995-

REPORT OF THE CHAIRMAN

Mr. Neil P. Rossmeissl
U.S. Department of Energy

INTRODUCTION

It was a very exciting year for the Hydrogen Agreement. The three active Annexes are now at the halfway mark of their three year work plans and are beginning to make some real progress. Although it was hoped that the Annexes would be further along, some of the activities of 1996 should help improve and expedite the progress so that the work is completed as scheduled.

A number of new activities were initiated in 1996, including a task on safety and an assessment of thermal hydrogen production. Other activities were continued, including the preparation of the comprehensive report on hydrogen road vehicles and a review of the potential to study bulk storage.

In addition to the standard reports on the progress of the Annexes, this year's Annual Report contains updates to the 1994 IEA Technical Report, "***Hydrogen Energy Activities in Eleven IEA Countries.***" For next year's report, the Executive Committee (ExCo) hopes to have completed an overview on the world's hydrogen energy activities.

MEMBERSHIP

There were thirteen active members of the Hydrogen Agreement during 1996: Canada, the European Commission, Germany, Italy, Japan, the Netherlands, Norway, Spain, Sweden, Switzerland, the United Kingdom, Turkey, and the United States.

The ExCo regrets to announce that funding cuts will result in Turkey no longer participating in the Agreement activities. The contribution of the Turkish representatives was a great benefit to the Agreement and they will be missed. The ExCo hopes to at least continue interacting with them informally and that perhaps the situation will reverse in the future, and Turkey will again be able to provide their expertise to the activities of the Agreement.

POTENTIAL NEW MEMBERS

Azerbaijan, Finland, Hungary, India, Israel, Korea, Mexico, New Zealand, South Africa, and Russia have expressed interest in participating in the Hydrogen Agreement. Specific representatives have been identified in India and Israel, and the Agreement will work to identify contacts for the other interested countries.

The ExCo will ensure that the respective governments of the interested parties are willing to commit to and support the activities of the Hydrogen Agreement. Once this confirmation is obtained, representatives will be invited to participate as observers in an ExCo meeting and the appropriate Annex meeting(s).

The ExCo looks forward to expanding its membership, particularly as future activities are being discussed and defined. The recent changes in IEA's restrictions on non-IEA member participants should result in the additional interest and the solidification of relationships with those non-member countries who have already expressed interest.

CHANGES IN THE ANNEX 12 OPERATING AGENT

After many years of participation in the Hydrogen Agreement, Mr. William Hoagland announced his resignation as Operating Agent for Annex 12, Metal Hydrides, to devote his time to some of his other hydrogen-related activities. Mr. Hoagland's excellent service will be missed. The ExCo expresses its gratitude for the outstanding contribution Mr. Hoagland made to the Agreements and hopes to collaborate with him on other projects in the future.

Dr. Gary Sandrock was unanimously appointed to replace Mr. Hoagland as the Annex 12 Operating Agent. Dr. Sandrock is the President of SunaTech, a New Jersey company active in the promotion and development of hydrogen systems, and has over 20 years of experience developing metal hydride materials and systems. Dr. Sandrock has been an active participant in Annex 12 and is responsible for developing the Metal Hydride Database. The Agreement is very fortunate to be benefitting from Dr. Sandrock's exceptional knowledge and leadership skills. His quick and efficient assumption of the Operating Agent responsibilities averted any delays in the progress of the Metal Hydride task.

CHANGES TO THE IMPLEMENTING AGREEMENT

One of the biggest undertakings of the ExCo over the past two years is the complete revamping of the Implementing Agreement in order to better provide for opportunities to involve Industry in the collaborative efforts of the Agreement. A major concern has been the ownership of patents and management of confidential and proprietary information. Historically, the Operating Agent was responsible for filing and maintaining patents. This has impeded interest from Industrial participants who are concerned with maintaining their competitive edge within their respective market. This switch to patent rights belonging to the inventing party, with the Agreement being able to license the technology, will provide a means for Industrial participants to join in the activities of the Agreement, while still benefitting from the opportunity to develop patentable results for which they may file for sole ownership.

This change to the Implementing Agreement was approved at the 1996 Spring ExCo meeting in Los Angeles, California. The entire, revised document is expected to receive unanimous approval at the 1997 Spring ExCo meeting.

HIGHLIGHTS OF THE 1996 EXECUTIVE COMMITTEE MEETINGS

The ExCo meets semi-annually to review the progress of ongoing work, determine the scope and direction of future work, and plan and review the budget. Below are the highlights of the meetings held during 1996:

35th Meeting in Los Angeles, California, United States, under the Chairmanship of Mr. Neil Rossmeissl (U.S. DOE) on May 8-10, 1996.

- The ExCo unanimously approved revisions to the Implementing Agreement, clarifying the definitions of confidential and proprietary information, and allowing for Intellectual Property rights, in the form of patents, to remain the property of the inventing party. This change should provide greater opportunities for Industrial collaborations.
- The possibility of combining with one or more of the other IEA Agreements was discussed as part of IEA's overall effort to reduce and streamline the number of Agreements. The ExCo unanimously decided that, at present, the greatest benefit would be achieved by aggressively pursuing collaborations with other, related Agreements, yet maintaining the Hydrogen Agreement as a separate, autonomous program.

- Mr. Addison Bain was identified as a potential expert on Hydrogen Safety that could be contacted to prepare a comprehensive report of international safety issues.

36th Meeting in Amsterdam, Netherlands, under the Acting-Chairmanship of Dr. Abraham Bahbout (European Commission) on November 12-15, 1996.

- A decision was made to complete the Hydrogen Road Vehicle report, including an update on changes in the field discussed at the World Hydrogen Energy Conference in Stuttgart, June 1996. This report will be published in early 1997.
- Mr. Katsuhiko Hayashi of Japan graciously accepted the position of Vice-Chair after a unanimous vote from the Committee. (The Hydrogen Agreement has two Vice-Chair positions. The other position is ably filled by Dr. Bahbout.)
- The Committee approved the first task of Mr. Bain's safety proposal. Work will commence in 1997.
- Mr. K. Joon of the Advanced Fuel Cells Agreement and Dr. Aldo Steinfeld of the SolarPACES Agreement both gave presentations on the activities of their respective Agreements and participated in discussions on potential areas for collaboration. The Annex 11, Integrated Systems, Operating Agent was given the task of working with the Fuel Cell Agreement to map out a more specific plan for collaboration. Likewise, the Annex 10, Photoproduction, Operating Agent and Mr. Steinfeld will work collectively to prepare a proposal for collaborative work between the Hydrogen and SolarPACES Agreements.

COORDINATION WITH OTHER ORGANIZATIONS

One of the founding principles of the International Energy Agency is that "collaboration on energy technology research and development, contributes to the economic development, energy security, and environmental protection objectives of Member countries." Due to the large number of Agreements in existence within the IEA, focus has been placed on reviewing the activities of all of the Agreements to identify areas where activities are being duplicated or where Agreements can be combined. As part of this effort, the Hydrogen Agreement participated in a joint meeting on Advanced Road Vehicle Technology and in the Fall meeting of the Renewable Energy Working Party.

Although a decision was made that the Hydrogen Agreement should remain as a separate Agreement, the ExCo is dedicated to working with all of the other related Agreements to ensure that the greatest benefit is achieved and the overall goals of the IEA are met. As part of this effort, representatives from the Advanced Fuel Cells and SolarPACES Agreements were invited to the Fall ExCo meeting in Amsterdam, Netherlands.

Advanced Fuel Cells: Mr. K. Joon of ECN, Netherlands, represented the Fuel Cell Agreement and presented a very educational tutorial on fuel cells as well as an overview of the Fuel Cell Agreement's activities. Mr. Joon also answered questions concerning industrial participation in the Fuel Cell Agreement, since several automobile manufacturers are active participants within that Agreement. There was consensus among the participants that a clear area for collaboration exists between the Fuel Cell Agreement and the Integrated Systems task. The Annex 11 Operating Agent, Mrs. Gregoire-Padró, will work with Mr. Joon and the appropriate Operating Agent(s) to improve the interface between the two Agreements, starting with a review of the respective work plans.

SolarPACES: Dr. Aldo Steinfeld from Paul Scherrer Institute, Switzerland, represented the

SolarPACES Agreement. Dr. Steinfeld discussed the Solar Chemistry Task in detail. A number of clearly defined areas were identified, under the heading of "hydrogen production," where collaboration would be beneficial, if not essential to both of the Agreements. As Annex 10, Solar Photoproduction of Hydrogen, is the most likely area for immediate collaboration with the SolarPACES Agreement, the Operating Agent, Mr. Gaudernack, was asked to act as the contact point for Dr. Steinfeld and to prepare a proposal discussing actions for collaboration.

Energy Conservation through Energy Storage: In August, the Chairman traveled to England to meet with Mr. John Baker of EA Technology, Capenhurst. Mr. Baker is the Operating Agent for Annex 9, Electrical Energy Storage Technologies for Utility Network Optimization, of the Energy Conservation through Energy Storage Agreement. As a result of this meeting, it was deemed beneficial for the Annex 11 Operating Agent, Mrs. Gregoire-Padró, to participate in the Experts Meeting on Electrolysis/Fuel Cells, sponsored by the Energy Storage Agreement, which took place November 21-22 in Orlando, Florida. Mrs. Gregoire-Padró ensured that there was no overlap in the modeling activities of her Integrated Systems task with those being discussed by the experts. Mrs. Gregoire-Padró also reported back to the ExCo on potential areas where information exchange might benefit the two Agreements.

Advanced Road Vehicles: Rapidly growing oil consumption has caught the world's attention. Of particular concern is the expected increase of road vehicles in developing countries such as China. If the current trends continue and technology does not improve dramatically, the demand for oil will surpass the available resources. Perhaps of even greater concern is the impact of the emissions from the increased number of road vehicles on the environment. This has been the driver for many of IEA's activities, including advanced fuels, hybrid and electric vehicles, light weight materials, and fuel cell research. This is also an area of great interest to the Hydrogen Agreement, as hydrogen is considered a "clean" fuel which could significantly reduce the amount of world-wide emissions from transportation.

IEA Headquarters has organized several Experts Meetings on Advanced Road Vehicle technologies, including one in March which was attended by the ExCo Secretariat, Ms. Carolyn Elam. These Experts Meetings bring together representatives from academia, industry, and the vehicle-related IEA Agreements. Although the current scope of the Advanced Road Vehicles activities is not directly tied to the activities of the Hydrogen Agreement, the ExCo will continue to participate in Experts Meetings whenever possible, and will work to collaborate with the Agreements on an individual basis.

Renewable Energy Working Party: The Agreement was asked to present a program overview at the 1996 Fall meeting of the Renewable Energy Working Party (REWP). The REWP was briefed on the operation, priorities, and strategy of the Agreement. The recent achievements and outreach activities were also discussed. At this briefing, the REWP was requested to take an active role in assisting the Hydrogen Agreement in its collaborative efforts.

Other Activities: The Hydrogen Agreement has also initiated plans for an Experts Meeting at which the Operating Agents and technical representatives from the related Implementing Agreements will meet and present their current Annex plans. This meeting should form the basis from which the different Agreements can develop collaborative work plans. A series of clear maps will be generated which identify contact points and a strategy for implementing collaborative work. The tentative plans for this meeting are for early- to mid-June 1997 at IEA Headquarters in Paris, France.

OUTREACH

A great deal of effort has been placed on outreach activities this year. Mr. Jonathan Hurwich of R.K. Sen and Associates attended the Spring ExCo meeting and gave an overview of the U.S. outreach program. As part of these activities, the U.S. Department of Energy completed its Hydrogen Program

Home Page on the World Wide Web, which includes a section devoted to the IEA Hydrogen Agreement. Outreach activities specific to the Agreement include:

- A brochure was prepared and distributed at the World Hydrogen Energy Conference (WHEC) held in Stuttgart, Germany, June 1996.
- Three presentations on IEA activities were made at the WHEC, two on activities related to Annex 10, and one on Annex 11.
- The Metal Hydride database went on-line on the World Wide Web and has undergone considerable expansion.

HYDROGEN ROAD VEHICLES REPORT

One of the strategies to achieve the goals of the Hydrogen Agreement is to produce reports on hydrogen technology subjects which will be used to disseminate information of value to researchers in the hydrogen energy field and to decision makers. Among the numerous subjects currently under investigation, the development of hydrogen road vehicles is the one that has triggered significant interest world-wide. The drivers for this interest include the significantly reduced environmental impact of such vehicles over existing technologies, the continuing advancements being made in the Fuel Cell industry, and the magnitude of the potential market. Every month brings its share of information on some new hydrogen vehicle project.

In 1995, the IEA Hydrogen ExCo commissioned the preparation of a State-of-the-Art report on hydrogen road vehicles as a means of not only reviewing the current technology, but also of disseminating information about hydrogen vehicles to the largest number of interested readers possible. A summary of the first draft of this report appeared in the 1995 Annual Report. Due to the recent emergence of a number of significant findings, such as those reported at the World Hydrogen Energy Conference in Stuttgart, the ExCo decided to forego publishing this report until early 1997.

The author, Mr. Thomas Doyle, has been with the Joint Research Centre of the European Commission at its Ispra Establishment for 23 years. His experience has primarily been in the nuclear field. Ten years ago he moved into a consulting role to different organizations, mostly involved with the environmental aspects of the energy industry. In the early 90's, he assisted in the management of the Euro Quebec Hydro Hydrogen Pilot Project, in drafting the technical specifications to the various public transport demonstration projects. He also became involved in R&D projects for hydrogen production from biomass and the hydrogen reduction of iron ore.

The IEA Hydrogen ExCo has no doubt this report will prove to be a useful tool to those, in one way or the other, involved with the development of hydrogen road vehicles and expresses its gratitude to Mr. Doyle for his insight into vehicle technologies.

SAFETY

The use of hydrogen in the metals, chemicals, glass, food, electronics, fertilizer, petroleum and space industries is well established. The range of uses has been increasing as has the consumption by specific application. Historically, hydrogen has had an excellent safety record. The many studies, R&D efforts, and experience base have contributed to the publication of regulations, standards, industrial data sheets and technical reports. Hydrogen safety is an issue of every aspect from production to utilization and continues to be of the utmost importance; not only to those researching, designing and working with it; but to the general public, local authorities, insurance agents, etc., as well.

There is unquestionably an international plethora of codes and standards that are directly, or in many cases indirectly, descriptive of hydrogen practices. An effort is underway (ISO TC 197 Hydrogen Technologies) to develop standards, but so far is focused on addressing issues of hardware, product quality, and facility designs. Another effort is underway in the U.S. (NHA Codes and Standards for the safe use of hydrogen energy) with a focus on components and systems, similar to the natural gas movement for standardization. Historically the industry (producers and distributor) is the acknowledged resident experts on hydrogen safety practices, but these details are not necessarily made public for a number of reasons.

Publications developed by the technical trade associations are numerous, but often are of limited scope and usually cross reference other documents for general information. The trail that the designer/operator has to follow to get a comprehensive story is time consuming, sometimes confusing, and worst of all results in an incomplete set of specific data. Another very important aspect is the fact that as new hydrogen demonstration projects get underway new data will be generated. This should be placed in some sort of common reference for the benefit of all. A single international guide may be the answer.

In an effort to address this, the ExCo has commissioned Mr. Addison Bain of the United States, to help in this effort. It is highly probable that an Annex will eventually be formed to follow through with developing a final publication and to implement a procedure for maintaining the safety information.

The first task of this work will be to canvas the U.S. industry, trade and technical associations, academia, insurance companies, fire departments, and government agencies to obtain opinions, recommendations, interest and willingness to share data and support this activity.

Mr. Bain is a recognized expert in the field of hydrogen safety. He spent over 30 years working for NASA and is currently a panel member of the Hydrogen Technology Advisory Panel to the U.S. Secretary of Energy. Additionally, he was the organizer of the National Hydrogen Association's Safety Committee.

SUMMARY

Again, it was a very productive year for the Hydrogen Agreement. Heartfelt thanks go out to Mr. Hoagland for his years of invaluable service and to the representatives from Turkey for their expert contributions to the Agreement. We welcome Dr. Sandrock as the Annex 12 Operating Agent and Mr. Hayashi as Vice-Chair and look forward to their insight into all of our activities.

A personal round of thanks goes out to Dr. Abraham Bahbout for stepping in on multiple occasions as the Agreement representative. His outstanding presentation to the Renewable Energy Working Party has ensured that the Hydrogen Agreement remains at the forefront of IEA's consciousness, and his assumption of the chairmanship responsibilities at the Fall ExCo meeting ensured a productive meeting and the initiation of a number of exciting activities.

The ExCo looks forward to coming year. Some of the exciting activities planned for 1997 include:

- planning and participation in an Experts Meeting on hydrogen-related IEA activities with the other related Agreements;
- completion of the first phase of the Safety task;
- publication of the Hydrogen Road Vehicle Report;
- publication of a comprehensive report on the Metal Hydride Database;
- initiation of a working group on Thermal Hydrogen Production;
- sponsorship of the BioHydrogen '97 conference, summer, Hawaii, by Annex 10.

OVERVIEW

Hydrogen Energy Activities in the IEA Hydrogen Agreement Member Countries

Carolyn C. Elam

National Renewable Energy Laboratory

INTRODUCTION

In December 1994, the Executive Committee of the IEA Hydrogen Agreement prepared and published a report on the *Hydrogen Energy Activities in Eleven IEA Countries*. This comprehensive report was the result of a June 1994 workshop at which the Executive Committee members shared information on hydrogen technology research, development and demonstration, and industrial activities in their respective countries. The goal of this workshop was to increase the awareness of policy trends, technical progress, research needs, and technical and non-technical barriers.

Several of the programs of the member countries have undergone substantial revisions since 1994, and thus the trends and policies discussed in the earlier report are no longer current. In an attempt to maintain an up-to-date awareness of hydrogen activities, updates from nine of the Agreement's member countries and the European Commission have been prepared and are included in this Annual Report. The updates entailed are from:

Canada	Norway
European Commission	Spain
Germany	Sweden
Japan	Switzerland
Netherlands	United States

KEY POLICY DEVELOPMENTS

As mentioned, a number of policy changes have occurred since the preparation of the 1994 report. Some of the "key" changes are summarized below:

- In Germany, hydrogen research activities have undergone considerable downsizing. The budget has been decreased from around DEM 20 million in 1994, to DEM 2.5 million for 1997. Historical support was based on the premise that large amounts of cheap electricity from renewable energy would be available in the near future. Because of the still very high costs of solar electricity, large-scale application of hydrogen will, in the foreseeable future, be obstructed by considerable costs or require high financial support. Thus the current policy is to maintain the state-of-the-art to provide this technology for niche uses or for large-scale application later on. Some key components are still under investigation including material research and efforts to reduce the cost of individual key components like electrolyzers and fuel cells.
- Although there is still no specific hydrogen program in Norway, recent events have resulted in increased support for hydrogen technologies. The deregulation of the Norwegian electricity market, combined with recent production shortages, has resulted in a significant increase in imports and, subsequently, prices. The result is a newly spurred interest in alternative energy sources, including hydrogen. This clear interest in hydrogen technology has manifested itself through the founding of a Norwegian Hydrogen Forum in September 1996. The objective of the Forum is to promote research, development and demonstration for hydrogen as an energy carrier in Norway, and stimulate international co-operation.
- In general, many of the programs are pushing more towards technology demonstrations.

NATIONAL PROGRAMS and FUNDING

The programs reported vary greatly in their size, funding, scope and length of existence. Several countries do not have formal hydrogen programs. Most, whether they have a formal program or not, have hydrogen related activities funded as part of other programs, such as fuel cells. Overall, funding for hydrogen research and development is still considerably less than for many other renewable energy technologies.

With the significant reductions to the German program, the United States and Japan stand apart as having the largest programs, with funding levels greater than USD 10 million. Germany, Canada, and Switzerland are the next closest in size with funding levels in the range of USD 1-5 million. (Note - the funding estimates for the above listed countries do not include the hydrogen related activities funded under other programs such as fuel cells or solar chemistry.) The funding levels for the Netherlands, Norway, Spain, and Sweden, all of which lack a formal hydrogen program, are estimated to be less than USD 1 million.

SIGNIFICANT ACHIEVEMENTS

A number of significant achievements in the area of hydrogen R,D&D have occurred over the last year. Some of the highlights include:

- In Canada, phase 2 of the fuel cell bus development program has resulted in the construction of a prototype 12-meter (40-foot) bus powered by a 205 kW (275 hp) proton exchange membrane (PEM) fuel cell engine. The bus is a zero emission vehicle and its driving characteristics are equal to or better than those of a diesel bus. The fuel cell engine occupies the same space as the diesel engine. The bus is fueled by hydrogen which is stored at 25 MPa (3600 psi) in composite cylinders located on the roof and has a range of 400 km (250 miles).
- In Switzerland significant progress has been made in the area of hydrogen production. Efficiencies of >4.5% have been achieved for the photolytic cleavage of both water and seawater with tandem cells. Advancements have also been made in the utilization of hydrogen in the catalytic synthesis of alcohols and amines.
- In the United States, a number of significant advancements have been made including the demonstration of a solar-to-hydrogen conversion efficiency of 7.8%, development of a new fiberoptic sensor with a detection time constant of 0.2 seconds and a recover time constant of 1 second, and completion of a Personal Utility Vehicle and portable refueling station.

CONCLUSIONS

In conclusion, there have been a number of recent changes in the national hydrogen programs of the IEA Hydrogen Agreement member countries. Subsequent Annual Reports will provide updates as program scopes and directions continue to change and major advances are achieved.

During 1997, the Executive Committee will be working to compile a comprehensive review of the major hydrogen related activities throughout the world.

CANADA

Hydrogen Energy Activities in Canada

*N. R. Beck and Martin Hammerli
CANMET Energy Technology Centre,
Natural Resources Canada*

NATIONAL POLICY

The mandate of the Hydrogen Energy Research and Development (R&D) Program of Natural Resources Canada (NRCan) is to develop and/or evaluate hydrogen systems for transportation and stationary applications, including off-grid applications. The Canadian National Hydrogen Program (CNHP) was initiated in the late seventies. The CNHP is managed by the CANMET Energy Technology Centre and includes fuel cell projects. Other federal government departments or agencies also contribute to hydrogen technology developments, including the Department of National Defense.

PROGRAM STRUCTURE

The program has three components:

- Hydrogen Production - the objective is clean, efficient hydrogen production from water electrolysis using renewable or sustainable energy sources.
- Hydrogen Utilization - the objective is to develop the technologies and processes required for hydrogen to be a safe and effective energy carrier.
- Fuel Cells - the objective is to further develop Canadian fuel cell technologies to lower costs and move towards commercialization. In addition, other fuel cell technologies will be evaluated and adapted for use in Canada.

FUNDING

The NRCan budget, which does not include money spent by other departments/agencies or the provinces, is currently at the level of about \$2.3 million per year (fiscal year 1996-1997).

RESEARCH, DEVELOPMENT AND DEMONSTRATION ACTIVITIES

Hydrogen Production

The main focus in hydrogen production is on improving alkaline water electrolysis technology.

Projects address:

- New amorphous alloy electrocatalysts.
- Improved separator development and testing for existing and advanced alkaline water electrolyzers, which will be operating at temperatures above the present 70-80°C for improved energy efficiency.
- The development of advanced electrolyser systems for large-scale electrolytic hydrogen production, with low capital cost, smaller footprint and improved energy efficiency.

- Fundamental investigation aimed at finding suitable new electrodes for a ceramic reversible high temperature electrolyser.

Hydrogen Utilization

Projects address:

- A small integrated power system has been built and tested successfully. The system includes a photovoltaic array, a battery bank for short-term energy storage, a hydrogen production/storage system, a fuel cell and a controller for automatic and remote control. Hydrogen gas is compressed to modest pressures and stored in a cheap container.
- The effects of adding a little hydrogen to the stream entering the catalytic converter of an internal combustion engine before it has reached its operating temperature, are measured quantitatively under various conditions. The anticipated environmental benefits are expected to be most significant on start-up, particularly on cold winter days.
- The development of low-cost magnetic refrigerants for use in a magnetic hydrogen liquefier is important because a magnetic liquefier has the potential of reducing the energy requirement by about a factor of two over the conventional compression/expansion method.
- Development of a hydrogen refueling system for near-term hydrogen vehicles. The objective in Phase 1 is to develop and test key components of such a hydrogen refueling system. The following items need to be integrated successfully: a hydrogen source; a filtering system to filter out any impurities in the hydrogen, e.g. water and oxygen; a compression unit; a storage unit; a nozzle/receptacle assembly; and a control system.
- Safety issues associated with large liquid hydrogen spills by a computer analysis approach followed by the design of a Spill Test Facility.
- Development of a new hydrogen sensor composed of a photopyroelectric palladium-polyvinylidene fluoride hydrogen detector element.
- Development of inexpensive hydrogen sensors and sensor interfaces for improving the operating efficiency and safety of small water electrolyzers, fuel cells, and hydrogen gas handling systems, including their use by consumers or located in consumer environments.
- Fundamental study of hydrogen embrittlement in austenitic stainless steels under dynamic load conditions.
- Non-destructive method, based on ultrasonic guided waves, is being investigated in a proto-type flaw detector.

Fuel Cells

Projects address:

- Production of a prototype low-cost new polymer electrolyte by Ballard Advanced Materials. Superior performance has been maintained, within an acceptable "aging" factor, for up to 5,000 hours at a

current density of 500 mA/cm².

- Fundamental studies on anode and cathode electrocatalysts, electrode structures, modeling, and water transport measurements in the PEFC.
- A pressurized test facility, capable of testing Solid Oxide Fuel Cell (SOFC) tubes up to 2 meters long at temperatures up to 1050 EC and pressures up to 15 atmospheres has been constructed at Ontario Hydro. Experiments with natural gas have been carried out over a range of operating conditions and with several Test Articles supplied by Westinghouse.
- A 200 kW Phosphoric Acid Fuel Cell (PAFC) Demonstration Power Plant, built by ONSI Corp., has been installed at Ontario Hydro's Central Regional Office, in Markham, Ontario. The PAFC Plant feeds AC electricity directly to the building in a load-following mode.

Significant Achievements

Phase 2 of the fuel cell bus development program has resulted in the construction of a prototype 12-meter (40-foot) bus powered by a 205 kW (275 hp) proton exchange membrane (PEM) fuel cell engine. The bus is a zero emission vehicle and its driving characteristics are equal to or better than those of a diesel bus. The fuel cell engine occupies the same space as the diesel engine. The bus is fueled by hydrogen which is stored at 25 MPa (3600 psi) in composite cylinders located on the roof and has a range of 400 km (250 miles).

OUTLOOK

Canada has some world-leading hydrogen-related technologies and the federal government will continue support for further development and implementation of these technologies.

Government funding is decreasing in general but the hydrogen budgets is relatively stable. Near term commercial opportunities need to be exploited to increase the industrial participation in the research program.

The major effort in fuel cells will continue to be directed at commercializing the Ballard PEM fuel cell technology.

EUROPEAN COMMISSION

Hydrogen Energy Activities in the European Commission

Dr. Abraham Bahbout

Joint Research Centre, Ispra

NATIONAL POLICY

The European Commission, under the instigation of the European Parliament, has been the first among the big powers to launch, since 1987, an important hydrogen program in collaboration with the Government of Quebec. The project has been called the "Euro-Quebec Hydro-Hydrogen Pilot Project" (EQHHPP), and is managed by the Directorate General of the Joint Research Centre.

The purpose of the project was to demonstrate the feasibility of Liquid Hydrogen (LH₂) transportation technologies and of various applications of hydrogen as an energy carrier.

No new funding for this project has been allocated since 1995, but many of the activities will have to be continued through the current and coming 2-3 years.

Since 1994, other activities indirectly relating to hydrogen technologies have been promoted by Directorate General XII, Brussels, under the Energy chapter "Joule" of the 4th Framework Program.

PROGRAM STRUCTURE

In addition to the European Commission program, there are national programs in a number of member states of the Union. Furthermore, substantial activities are also undertaken by the private sector.

RESEARCH, DEVELOPMENT AND DEMONSTRATION ACTIVITIES

The EQHHPP has primarily funded cost-shared, demonstration projects, but has also funded a number of system studies and studies of a few topical issue.

- The system studies included the identification and definition of demonstration opportunities.
- Topical studies concerned the external and social costs of energy usage in the Public Transportation Sector with special Focus on Road Transportation; the investigation on safety, regulations and acceptability of hydrogen; and the storage of hydrogen by adsorption.

Demonstration projects concerned the following items:

- *A City bus with a converted diesel internal combustion engine (ICE) and LH₂ storage.* The bus, a Van Hool with a MAN ICE engine, was completed by Hydrogen Systems N.V., St.-Truiden, Belgium, in July 1994. A new version is presently being assembled with a Van Hool A 308 and a T 7400 Crusader engine. This bus will be demonstrated during the autumn and winter of 1997.
- *A City bus with a converted natural gas ICE and LH₂ storage, by MAN, Nürnberg, Germany.* The bus has been circulating, in regular service and with passengers on-board, since April 1996 in Erlangen.

- *A City bus with a fuel cell and batteries, and LH₂ storage.* The bus, a Macchi-Ansaldo engineered by Ansaldo Ricerche, Genoa, Italy, will be equipped with a first generation De Nora- Permelec fuel cell. The bus is due to circulate during the spring and summer of 1997.
- *A passenger boat powered by a fuel cell with LH₂ on-board storage.* The boat is being engineered by Ansaldo Ricerche, Genoa, Italy; with a second generation De Nora-Permelec fuel cell. It is due to be ready for circulation on the Lago Maggiore, north of Italy, in April 1997.
- *Safety tests: Spilling of LH₂, by BAM, Berlin, and crash tests of LH₂ car tanks, by BMW.* The tests have been completed.
- *Experimental evaluation and analytical modeling of low NOx hydrogen combustors for aero engines.* This work is performed by a number of companies, mainly of the Daimler-Benz Group (Germany), in collaboration with P&WC (Canada) and UTRC.
- *Design, construction and testing of a 60 m³ LH₂ storage tank.* This work is conducted by a group of industries, including Air liquide, TNSW and BAM. The project is now being completed.
- *Co-generation of electricity and heat, in an urban site in Hamburg, Germany, with an ONSI type fuel cell, fed directly with hydrogen.* The demonstration has been delayed because of the time requirements for obtaining a licence for the storage, on site, of LH₂. The work is being conducted by HEW and GEW.
- *Construction, testing and certification of a prototype LH₂ container, in collaboration between a manufacturer from Quebec and the German companies Germanischer Lloyd and BAM (Hamburg), Berlin.* The project is still in its initial phase.

Under the Joule Program, four different fuel cell types of vehicles are under development:

- A Renault Laguna car, with LH₂ storage, to be ready by April 1997.
- A Peugeot car, with compressed hydrogen on-board, to be ready in 1999.
- A Volkswagen car, with a methanol reformer on-board.
- A second generation fuel cell bus, with Neoplan (Germany), De Nora-Permelec (Italy) and Air liquide (France), to be ready for mid 1999.

FUNDING

The total funding by the European Commission for the EQHHPP has been approximately 21.6 Millions ECU. The European Industry has matched this effort with a total of 1711 Million ECU.

The total value of the contracts under Joule is more than 15 Million ECU.

COMMERCIAL ACTIVITIES

All the demonstration projects, under the EQHHPP and the Joule Program, are funded on a cost-shared basis and are carried out by industrial groupings, with partners from at least 2 different member states of the European Union.

Under the General Conditions of such contracts, the information generated in the course of the work is owned by the contractor who generates such information. The contractor is bound to develop, exploit or

commercialize the results in conformity with the interests of the Union, within a reasonable period of time to be agreed upon with the Commission.

Some of the contractors have already capitalized on the information generated, by selling components based on their acquired knowhow.

OUTLOOK

There are indications that a hydrogen program will be included in the future fifth Framework program of the European Commission, focusing on urban applications.

GERMANY

Hydrogen Energy Activities in the Federal Republic of Germany

P. Malinowski

Project Management Organisation

Biology, Energy, Ecology (BEO)

Research Center Jülich GmbH

NATIONAL POLICY

The intensified R&D work on a hydrogen economy was based on the expectation that large amounts of cheap electricity from renewable energy will be available in the near future. Only then, the need for hydrogen as an energy transport medium and temporary energy storage medium would become relevant (although it would always have to compete with electricity).

Today, after more than 15 years of extensive research, this forecasted development cannot be confirmed, mainly because of the still very high costs of solar electricity. Major research and development goals have been reached and the components needed for clean production and utilization of hydrogen are available. However, large-scale application will, in the foreseeable future, be obstructed by considerable costs or require high financial support. According to present knowledge, it will take at least another 30 to 50 years for hydrogen to become an economically important part of energy systems. It was therefore decided that it is no longer justified to continue supporting hydrogen research and technology in such a broad manner.

Nevertheless the aim should be to maintain the state-of-the-art to provide this technology for niche uses or for large-scale application later on. Some key components of hydrogen technology must be developed further using new results of basic research, such as materials research. Continuous experimental operation of "key components" should help to gain operational experience. Another important challenge is to reduce costs of individual key components like electrolyzers and fuel cells.

PROGRAM STRUCTURE and FUNDING

Hydrogen activities in its reduced form are still part of the 4th Program of Energy Research and Energy Technology of Federal Ministry of Education, Science, Research and Technology (BMBF) and belong to the subchapter "Renewable Energy Sources and Rational Energy-Use".

German federal support in past years focused on the following subjects:

- Carbon dioxide-free production of hydrogen from water using electricity generated by means of solar energy, in particular, development of improved techniques of hydrogen production, mainly of electrolyzers with high efficiencies.
- Development and testing of hydrogen-fueled road vehicles, for example an experiment with a pool of hydrogen-fueled road vehicles conducted in Berlin (1984-1988) proved successful.
- Hydrogen use for electricity generation by means of fuel cells, for heat generation in gas heating boilers and catalytic heating systems, as well as for cooling in catalytic cooling systems.

Since 1980, BMBF has been providing funding for hydrogen technologies amounting to DEM 160

million.

Furthermore, components such as electrolyzers and fuel cells, and their combination with photovoltaic conversion systems, have been tested in the German-Saudi Arabian cooperation project HYSOLAR, which was concluded in late 1995 after a duration of 10 years. Solar Wasserstoff Bayern (SWB), a demonstration project in Neunburg vorm Wald (Bavaria), was initiated 10 years ago and will be funded by BMBF until 1999. Presently, it seems not justified to start further R&D and demonstration projects concerning solar hydrogen technology.

The present funding of hydrogen activities for 1997 amounts to DEM 2.5 million. By comparison, fuel cell funding adds up to DEM 22 million for 1997.

RESEARCH, DEVELOPMENT AND DEMONSTRATION ACTIVITIES

From a once quite voluminous hydrogen research program (funding in 1990-91 DEM 17-18 million/year), only two projects are being followed in 1997:

- SWB (Solar hydrogen production and application), a demonstration project where the developed components of the hydrogen economy system are still being tested.
- The cost reduction program of the newly developed, advanced water electrolyser is carried out.

COMMERCIAL ACTIVITIES

Further interest of the companies in newly developed products, such as electrolyzers and hydrogen-fueled buses, decreases towards a minimum once the projects and the financial support terminate. The argument behind this is that no market penetration possibilities exist in the near- and mid-term future.

OUTLOOK

There exist large markets for hydrogen as a chemical raw material and for upgrading heavy oils and coal. Nonetheless, as long as hydrogen is produced from oil, gas or coal; or via electricity from oil, gas or coal, and even hydro; there is no chance to introduce hydrogen into the energy market. There are, however, many other applications for electrolytic hydrogen. For relatively small demands, 10 m³ and upwards, there are applications for electrolysis of water for various reduction processes, fat hardening, float glass production, semiconductor manufacturing, high purity refining of certain metals and for power station generator cooling.

The direct use of hydrogen in a "Hydrogen Economy" is considered to be a long-term option to solve energy supply as well as pollution problems. The role of hydrogen in the energy economy will be, if at all, always complementary to electricity. For the short- and mid-term, energy savings and the rational use of energy will play the major part in the needed reduction of carbon dioxide emissions. If there is a considerable increase in the cost of fossil fuels and the need for even greater carbon dioxide reduction, there might be a renewed interest in the electrolytic production of hydrogen. However, the possibilities of non-fossil hydrogen as a potential energy carrier for the future should not be over-estimated.

JAPAN

Hydrogen Energy Activities in Japan

Katsuhiko Hayashi

Agency of Industrial Science and Technology (AIST)

Ministry of international Trade and Industry

NATIONAL POLICY

The Agency of Industrial Science and Technology (AIST) Ministry of International Trade and Industry, started the New Sunshine Program in 1993. The objective of the New Sunshine Program is to develop innovative technologies to create sustainable growth, while solving energy and environmental issues. The main hydrogen projects are carried out under this program. The primary hydrogen related activities in the New Sunshine Program are listed as follows:

- International Clean Energy System Technology Utilizing Hydrogen (WE-NET)
- Environmentally Friendly Catalysts
- Environmentally Friendly Technology for the Production of Hydrogen

PROGRAM STRUCTURE

WE-NET project started in FY1993. Although the concept of the project consists of three phases for twenty-eight years in total, the basic plan of Phase I (FY1993-FY1998) of the program is authorized. The project on Environmentally Friendly Catalysts started in FY1992 and is scheduled to continue until FY2001. The project on Environmentally Friendly Technology for the Production of Hydrogen started in FY1991 and is scheduled to continue until FY1998. The basic plans of these projects have been determined and authorized by AIST and directly administered by the New Energy and Industrial Technology Development Organization (NEDO). In the case of the WE-NET project, the major part of the R&D is carried out by private companies on a consignment basis with NEDO and the national research institutes in AIST.

FUNDING

These projects are mainly carried out by subsidization from AIST to NEDO. In the case of the WE-NET project, the budgets are also given to the national research institutes. The budgets for the projects are as follows:

WE-NET project

- 4.48 billion yen (FY1993-FY1996)

The project of Environmentally Friendly Catalysts

- 1.44 billion yen (FY1992-FY1995)

The project of Environmentally Friendly Technology for the Production of Hydrogen

- 1.79 billion yen (FY1991-FY1996)

RESEARCH, DEVELOPMENT AND DEMONSTRATION ACTIVITIES

WE-NET Project

The ultimate aim of the project is to build a world energy network where renewable energy can be converted into a secondary, transportable energy in the renewable energy-rich regions, then transported to and utilized in an energy consumption region. In Phase I, core technologies such as hydrogen production, hydrogen storage and transportation, and hydrogen utilization, as well as the optimum design of the energy network system is being carried out.

Hydrogen Production

For hydrogen production technology, Solid Polymer Electrolyte Membrane Water Electrolysis (PEM electrolysis) technology is under development. The target in Phase I is to develop PEM cells with energy conversions greater than 90%, at the current density of 1 A/cm², and with an electrode area of 2500 cm². A few types of cells with efficiencies of over 90%, at the current density of 1 A/cm², and with an electrode area of 50 cm², have already been developed.

Hydrogen Storage and Transportation

For hydrogen storage and transportation, the R&D on technologies for liquefaction, large scale hydrogen storage and seaborne transportation, and storage and transportation by hydrogen absorbing alloys is carried out.

- Hydrogen liquefaction development is focused on the design and evaluation of high-performance hydrogen liquefaction processes which can generate 300 tons/day liquid hydrogen (LH₂).
- A hydrogen tanker for transportation of 20,000 m³ of LH₂ and a hydrogen storage tank with a capacity to store 5,000 m³ of LH₂ being investigated. In particular, this work is focused on insulation technologies in order to prevent thermal invasion.
- The mechanical properties of cryogenic structural materials are also researched. The current activity is to carry out mechanical tests on the base metal and welded metal of the cryogenic structural materials in both gaseous hydrogen and liquid helium atmospheres.
- New hydrogen absorbing alloys for hydrogen transportation and storage systems are researched. The current activity is to survey the potential of a new high-performance hydrogen absorbing alloy which has a hydrogen storage capacity of over 3 wt%, under a dehydrogenating temperature of 100°C or lower.

Hydrogen Utilization

For large scale hydrogen utilization systems, the core technologies to enable the use of hydrogen combustion turbines with thermal efficiencies of over 60%, at a turbine inlet temperature of 1700°C, are development. The current activities are:

- Design of the optimum plant cycle;
- H₂/O₂ combustion technologies;
- Cooling structures of the turbine blade and rotor;
- High temperature heat exchangers;
- High-temperature resistant materials which can endure at turbine inlet temperatures of 2000°C.

At the same time the R&D on small scale hydrogen utilization systems is carried out. The current activity is to survey a hydrogen-fueled co-generation system, a hydrogen-transportation system using an oxygen-hydrogen fuel cell and a hydrogen combustion engine, and hydrogen supplying systems.

The Project on Environmentally Friendly Catalysts

The project on environmentally friendly catalysts aims at developing new catalysts which enable high selectivity and activity at ordinary temperatures and pressures. One of the activities is to develop photo-catalysts that can split water, leading to the formation of hydrogen

The Project on Environmentally Friendly Technology for the Production of Hydrogen

The project of environmentally friendly technology for the production of hydrogen aims at developing technologies for the efficient production of hydrogen using microorganisms. Currently, the main activities are:

- Screening of microorganisms having superior hydrogen production capabilities.
- Developing optimization techniques for a hydrogen producing bioreactor.
- Development of a system integration.

COMMERCIAL ACTIVITIES

Private companies (TOYOTA MOTOR CORPORATION and MAZDA Co Ltd.) have been researching hydrogen fueled automobiles. They have fabricated hydrogen-fueled automobiles utilizing hydrogen absorbing alloy tanks.

OUTLOOK

All of these projects are now fully underway. The results of the R&D work are expected to contribute to the promotion of the overall New Sunshine Program.

NETHERLANDS

Hydrogen Energy Activities in the Netherlands

Antoon H.M. Kipperman

*Netherlands Agency for Energy
and the Environment (NOVEM)*

NATIONAL POLICY

In the Netherlands several Hydrogen related projects are carried out. These activities are part of the national energy program, so there is no separate national program on Hydrogen as such.

In the national policy the starting point is the long-term reduction of carbon dioxide emissions. A comprehensive study on this item has been carried out by the Netherlands Energy Research Foundation (ECN). The environmental department (M) of the Ministry of VROM, initiated several proposals for hydrogen projects through the Centre for Energy Saving (CE) in the framework of the carbon dioxide reduction program.

PROGRAM STRUCTURE and FUNDING

Starting in 1994, hydrogen is explicitly mentioned in the program New Energy Conversion Technologies (NECT), which NOVEM is executing for the Ministry of Economic Affairs. This is a five year program, with a yearly update.

Energy systems are mentioned as a very particular item in the NECT program as a basis to relate separate activities, including hydrogen. It is obvious that this system approach will be the guideline for consideration of individual R&D proposals.

In this NECT program several projects on the use of hydrogen as a possible fuel in burners are under execution. The connection of NECT to the Fuel Cell program is beneficial to these activities.

Of the total funding for the projects on burning, some 0.2 M NLG (0.1 M \$) can be identified as related to hydrogen activities. For the energy system activities, a total budget of about 0.2 M NLG (0.1 M \$) is allocated to hydrogen activities and will be increasing during the five years of the program to about 0.3 M NLG (0.15 M \$).

RESEARCH, DEVELOPMENT AND DEMONSTRATION ACTIVITIES

In the aforementioned study on carbon dioxide reduction, one of the strong options that has resulted in the various scenarios is the application of hydrogen as a fuel. Due to the fact that hydrogenation of bio-hydrocarbons was not included as a technology, clean hydrocarbon fuels were not identified by the computer program. Further analysis, however, on this hydrocarbon option showed that this is an attractive opportunity for a rapid application into the existing infrastructure.

The research and development of advanced burners started around 1987 and was oriented towards low NO_x emissions and high efficiencies. This resulted in a fully pre-mixed ceramic foam burner, which

turned out to be well adaptable to a variety of gasses including pure hydrogen. Since 1993 a special project has run on the application of hydrogen rich fuel gas (to 100%). This project has been successfully terminated,

Fuel cells are also under investigation in a renewed program on the development of Molten Carbonate Fuel Cells (Advanced DIR-MCFC) started in early 1996 by a cluster of participants from research institutes (ECN), industry (STORK and De SCHELDE) and NOVEM, and supported by the European Commission. Applications in which residual hydrogen is used, are under consideration for the short term either with this MCFC or other available fuel cells. The budget for these developments (running from 1986) amounts some 250 M NLG (125 M \$) for a period to 1999.

Support Activities

■ Government Subsidies and Incentive Programs

In addition to the above mentioned projects the development of a small advanced turbine (1.5 MW) is subsidized. For this turbine, chemically recuperated natural gas, i.e. a mixture of CO and H₂, has been considered as well. According to the engineers pure hydrogen should also be possible. The financial support amounts to some 6 M NLG (2 M \$) for the entire development until 1998.

- Within the framework of the national carbon dioxide education plan, several hydrogen demonstration projects have been proposed. Once demonstration projects are selected, additional standards and certification activities will be initiated.

COMMERCIAL ACTIVITIES

To date, commercial activities have been restricted to the hydrogen ceramic foam burner.

OUTLOOK

In the Netherlands the approach is to implement hydrogen gradually into existing energy systems. This provides the best opportunity for a successful implementation in the short term. Current and new developments of components and technologies should fit into this approach and are therefore checked against the requirements of such hydrogen-based systems. Implementation of residual hydrogen from chemical industries in such systems is now under consideration in a first project with fuel cells. It has turned out to be more profitable to apply an advanced burner concept with modified control system, rather than using the hydrogen in fuel cells.

NORWAY

HYDROGEN ENERGY ACTIVITIES IN NORWAY

*Bjørn Gaudernack
Institute for Energy Technology*

NATIONAL POLICY

Although several hydrogen-related projects are being carried out there is no specific national hydrogen program in Norway. The energy situation in Norway is rather unique, with electricity production based exclusively on hydropower and a large export of oil and natural gas. This implies that much of the energy-related research, development, and demonstration is focused on hydroelectricity and petroleum technology.

However, some recent events may have changed the picture somewhat. The Norwegian electricity market has been deregulated, and last year a production shortage occurred. This resulted in increased imports and rising prices, and also spurred an interest in alternative energy sources. A decision to build two gas-fired power stations caused considerable controversy, since it is clear that Norway will not be able to fulfill its ambition of stabilizing CO₂ emissions on the 1990 level in year 2000. These factors seem to have stimulated the interest in renewable energy and clean energy carriers, like hydrogen.

Several politicians have made statements, in Parliament and elsewhere, to the effect that development of alternative energy sources and cars should be stimulated. Increased support of hydrogen projects has been specifically mentioned. The clear interest in hydrogen technology existing within scientific and industrial environments, has manifested itself through the founding of a Norwegian Hydrogen Forum in September 1996. The objective of the Forum is to promote research, development and demonstration for hydrogen as an energy carrier in Norway, and stimulate international co-operation.

Norway's participation in IEA's Hydrogen Program is funded by the Research Council. Apart from serving as Operating Agent for Annex 10, Norway participates in Subtask B of this Annex and also in Annex 12. Participation in a JOULE 11 project involving hydrogen is supported by the Research Council, Norwegian Industry and the European Commission. A bus demonstration program is being supported by the NYTEK program as well as other authorities and industrial partners.

FUNDING

Funding through the Research Council amounted to about 2 million NOK (0.3 MUSD) in 1996, Funding of research, development and demonstration activities by industry and other sources cannot be assessed accurately. It can be roughly estimated at 1 MNOK (0.15 MUSD).

RESEARCH, DEVELOPMENT AND DEMONSTRATION ACTIVITIES

The main government-sponsored activities in Norway are:

- A strategic program conducted by the Institute for Energy Technology (IFE). This includes participation in the IEA Hydrogen Program and in the JOULE Project mentioned above. It also includes modeling and experimental studies of stand-alone power supply systems (SAPS) and of wind energy utilization.

- Metal hydride development is carried out at IFE, contributing to Annex 12 of IEA's Hydrogen Program. IFE and NTNU cooperate in this area and participate in a cooperation between Nordic countries. The metal hydride research and development will expand from 1997 on.
- The Agder College in Grimstad is engaged in mathematical modeling of metal hydrides, and development of electrode materials for hydrogen evolution.
- The Norwegian University of Science and Technology (NTNU) in Trondheim is engaged in development and testing of metal hydrides for batteries. There is also research and development on water electrolysis, sponsored by the NYTEK program and Norsk Hydro. So far only alkaline electrolyzers have been studied, but it is planned to expand the studies to include also polymer electrolytes.
- At the University of Oslo 's Physics Department several hydrogen-related projects have been carried out, such as PV-based water electrolysis and metal hydride storage. At present some fundamental studies of hydrogen-metal systems are going on. There is a cooperation with IFE on the development of stand-alone systems.
- The Norwegian Institute for Water Research (NIVA) has a large culture collection of cyanobacteria, and studies photoproduction of hydrogen by such microorganisms. This is part of a more comprehensive project on algal technology, and contributes to Subtask B, Annex 10 of IEA's Hydrogen Program.
- A hydrogen bus demonstration program is being planned by two companies in the Oslo area and several industrial companies. The project involves purchase and operation of four hydrogen (ICE) powered transit buses. They will be built by MAN in Germany, and will be similar to the prototype now operating in Erlangen. Hopefully, the first bus will be delivered during 1997.

COMMERCIAL ACTIVITIES

Norsk Hydro has a long tradition in electrolytic hydrogen production, but practically all industrial hydrogen production is now based on steam reforming of hydrocarbons. Most of the hydrogen goes into ammonia produced in Norway and in factories abroad. A large methanol plant, operated by the government-owned oil company Statoil, will start production this year.

Norsk Hydro Electrolyzers have a good position in the world market for water electrolyzers and see increasing business opportunities, especially in Asia. Their technological basis is alkaline electrolyzers which they continue to improve, but they also keep an eye on alternative technologies. Another Norsk Hydro subsidiary, Hydro Megon, is engaged in rare earth and misch-metal production, and has a active interest in the development of metal hydrides.

The "CB&H" (Carbon Black and Hydrogen) process developed by Kvaerner Engineering has received a lot of publicity and attention world-wide. Kvaerner is now planning commercial activities, and is at present negotiating with Canadian authorities about building a "CB&H" plant near Montreal.

OUTLOOK

The considerable interest in Norway, both in industry and elsewhere, for hydrogen as an energy carrier, may be based on the long tradition of industrial hydrogen production, the existence of state-of-the-art technology, and realization of the potential that this country holds for production and export of hydrogen. Also, there is a general awareness of the increasing environmental problems, demanding new and cleaner energy sources and carriers. The political climate seems to be changing in favor of

increased support for hydrogen activities.

However, the resources are limited in the research and development supporting system, and hydropower as well as petroleum activities are important for Norway. Thus, one cannot expect a sudden breakthrough for hydrogen, but probably gradually increasing support. The first significant application is likely to be in the transport sectors since this will be relatively easy to implement, and will have a significant effect.

SPAIN

Hydrogen Energy Activities in Spain

Antonio G. García-Conde
INTA

NATIONAL POLICY

At present, there is no formal national program for hydrogen energy in Spain. INTA has been running activities since 1988 in the areas of hydrogen production, storage and utilization. All of the projects have been funded by the Ministry of Defense and have received subsidies from the regional government of Andalusia (south of Spain).

PROGRAM STRUCTURE

The INTA program on hydrogen technologies had two main objectives, as defined in 1989:

- The use of hydrogen as a storage medium for solar electricity.
- The use of integrated systems, Solar PV- Electrolysis Fuel Cell, for space manned missions.

The space related activities were abandoned on 1993. Since 1994, hydrogen activities were concentrated on the utilization of hydrogen in fuel cells looking for both a non-centralized electricity generation (services sector) and a clean fuel for transportation.

RESEARCH, DEVELOPMENT & DEMONSTRATION ACTIVITIES

Pilot plants for solar hydrogen production and storage were evaluated and are now in use for hydrogen production for utilization in fuel cells (phosphoric acid and proton exchange membrane).

The main characteristics of the above mentioned pilot plants are the following:

- 8.5 kWp photovoltaic field
- 5.2 kW alkaline electrolyser
- 24 m³ metal hydrides (TiMn₂) storage
- conventional pressurized gas installation for bottles of 8.8 m³ at 200 bar

A phosphoric acid fuel cell (PAFC) system is under evaluation. The PAFC yields 10 kW of electrical power at 90 V and 112 A and provides hot air at 180°C. A comparison of the system performance operating the fuel cell with reformed methanol and pure hydrogen will be carried out.

An experimental facility to evaluate the performance of a Proton Exchange Membrane Fuel Cell (PEMFC), under simulated operation of a typical urban car, has been constructed. A 2.5 kW PEMFC stack was installed during 1996. A new 5 kW stack will be installed on 1997.

INTA is participating as a partner in the preparation of a project, named European Integrated Hydrogen Project (EIHP), focused on reaching a harmonize approach for the licensing and approval of hydrogen

related vehicles, infrastructural equipment and components. The proposal will be presented at the end of January 1997 to the JOULE Program of the General Directorate for Science, Research and Development within the European Commission.

FUNDING

The below table indicates a rough estimate of the investments and subsidies provide for the studies and piloting activities of the INTA program on hydrogen technology.

Year	INTA (Investment)*	Regional Government (Subsidies)*
1994	19.75	7.5
1995	10	5.2
1996	10	4.5

* (10⁶ Pts)

COMMERCIAL ACTIVITIES

At present, there are no commercial activities in Spain concerning hydrogen as a future energy carrier.

OUTLOOK

The Center for Energy and Environment Research (CIEMAT), which comes under the Spanish Ministry of Energy and Industry, is expected to have the next major involvement in hydrogen related activities.

Within the CIEMAT organization, the Institute for Conventional Energy Technology (ITEC), carries out activities on hydrogen generation for the conversion of fossil fuels. At this institute, projects on reforming, partial oxidation and gasification processes are managed. In addition, ITEC is running a program on fuel cell research and development. Representatives of the ITEC have announced the initiation of activities focussed on the utilization of hydrogen to supply fuel cells.

On the other hand, INTA is focussing its hydrogen activities on the transportation sector. INTA, as an official organization for vehicles certification and homologation, works to prepare a minimum regulation basis for the utilization of hydrogen in vehicles. It is a mid- to long-term activity which should start, in the short-term, by developing standards and licensing procedures to regulate the use of natural gas in vehicles.

The utilization of hydrogen as a storage medium for renewable electricity and the role of hydrogen in the development of renewable energies in Spain are aspects that still have to be assessed with the Spanish authorities.

SWEDEN

Hydrogen Energy Activities in Sweden

Wiktor M. Raldow

Department of Generic Technologies

NUTEK - Swedish National Board

for Industrial and Technical Development

NATIONAL POLICY

The current hydrogen R,D&D policy in Sweden can be characterized as active, world-wide monitoring of technology development. The implementation of this policy is accomplished by funding a limited number of high-quality research projects and case-studies within the field and by participation in international cooperation. IEA Hydrogen Production and Utilization Implementing Agreement is considered to be of crucial importance in this context.

PROGRAM STRUCTURE and FUNDING

There is no common funding for the field of hydrogen in Sweden, with the exception of a relatively small amount of money for international cooperation and case studies which is administered by NUTEK (Swedish National Board for Technical and Industrial Development). Other agencies, such as the Swedish Natural Science Research Council (NFR) and the Swedish Research Council for Engineering Sciences (TFR), provide funding for hydrogen related projects based on their own priorities. There is some interest from industry for conducting feasibility studies for specific energy applications.

The Knut and Alice Wallenberg foundation supports a collaborative research program intended to develop biomimetic metal-organic supercomplexes for hydrogen production (or other energy-rich compounds) based on the principles of natural photosynthesis.

It should be noted that the Swedish fuel cell program is not covered in this report since it is a part of another IEA Implementing Agreement.

RESEARCH, DEVELOPMENT AND DEMONSTRATION ACTIVITIES

Major RD&D activities within the field are conducted at universities and can be characterized as basic research. The groups involved are as follows (the groups active in the artificial photosynthesis program are indicated by "**"):

Dr. D. Noréus, University of Stockholm

☐ Metal hydrides for energy storage applications, batteries

Prof. B. Åkermark, the Royal Institute of Technology, Stockholm*

☐ Synthesis of organic supercomplexes for hydrogen production

Dr. P. Lindblad, University of Uppsala

☐ Hydrogen metabolism in cyanobacteria

Prof. M. Almgren, University of Uppsala*

☐ Photochemistry

Dr. S.-E. Lindquist, University of Uppsala*

☿ Photoelectrochemical methods for hydrogen production

Dr. B. Hjörvarsson, University of Uppsala

☿ Hydrogen in films, multilayers and superlattices

Dr. Y. Andersson, University of Uppsala

☿ Structural studies of metal hydrides

Prof. L.-G. Ekedahl, Linköping University

☿ Directional processes over membranes

Dr. H. Dannetun, Linköping University

☿ Hydrogen in catalytic reactions on metal surfaces

Dr. A. Krozer, Chalmers University of Technology, Gothenburg

☿ Kinetics of hydrogen uptake, catalytic combustion

Prof. S. Styring, University of Lund*

☿ Photobiological and chemical methods for hydrogen production

COMMERCIAL ACTIVITIES

Production of hydride batteries has recently started in Sweden with the aim of providing low cost, environmentally compatible batteries for appliances such as mobile telephones. The enterprise, supported by Ericsson, Gylling, Telia, Electrolux, IMRA R&D Japan, and NUTEK, is named NiMe Hydrid AB and located in Mönsterås.

OUTLOOK

Sweden will continue to support basic research projects, with emphasis on hydrogen production; some efforts will be directed towards case studies and demonstration activities. The level of activities may be increased, however, in the new emerging energy technologies R&D-program proposed in order to facilitate the process of phasing out nuclear energy in Sweden.

SWITZERLAND

Hydrogen Energy Activities in Switzerland

Armin Reller

Swiss Federal Office of Energy

NATIONAL POLICY

In the Swiss National Energy Research Program, hydrogen is considered as an important potential energy carrier and chemical commodity. Therefore, Switzerland keeps track of possibilities for the sustainable production, storage and utilization of hydrogen. The main goals are the regional regenerative production (the conversion of solar radiation into hydrogen by different processes), the substitution of fossil fuels by hydrogen and the utilization pathways simultaneously produced by-products. Owing to the fact that the implementation of hydrogen technology is often hampered by engineering, handling and safety problems, considerable efforts are directed towards new materials and materials science as key disciplines for an efficient development of hydrogen technology. Consequently, a paramount task of the program manager, Armin Reller, consists in identifying niches where hydrogen technology can be implemented in an economically and strategically reasonable way. These niches include the utilization of hydrogen as a chemical commodity, i.e. as a reducing agent in technical processes, but also as a fuel for high-temperature processes, where any trace of carbon or carbon oxides would effect or even deteriorate the properties of the products.

Research activities are carried out by closely interacting teams from public research institutes and industry. The projects are subject to a short-, mid-, and long-term perspective. This is very important with respect to the financial and economic constellations governing the technical or industrial implementation of any process.

The Swiss research and development activities are clearly associated with international programs, above all with the IEA activities and the research and development programs of the European Commission. The present and future policy aims at identifying and realizing strongholds of activities rather than supporting a too large spectrum of widespread and dispersed projects.

PROGRAM STRUCTURE

Research and development activities in the field of Hydrogen Energy and Technology are financially supported and logistically coordinated by the Swiss Federal Office of Energy. Federal and cantonal research institutes, as well as private institutions and industries, guarantee additional financial support. In the near future an enhanced coordination with research projects of the Swiss National Science Foundation is envisaged in order to create an optimum structure ranging from fundamental research to technical realization including process engineering.

As it is shown in the table of projects, the main activities are carried out at the Paul Scherrer Institute, within an alliance of three research teams located at the Universities of Bern, Lausanne and Geneva, as well as within an alliance of two research teams located at the universities of Fribourg and Geneva. The Hydrogen Energy Program is divided into four segments:

- Hydrogen production based on regenerative energy sources, in particular solar energy;

- Hydrogen storage and transportation technologies;
- Hydrogen utilization as a fuel and chemical commodity;
- Supporting activities such as materials science, demonstration and educational activities.

FUNDING

The total public funding is about six million SFr per year (30% Federal Office of Energy, 35% Board of the Swiss Federal Institute of Technology, and 35% Cantonal Universities). Private funding is less than half a million SFr per year. The projects may be proposed by any individual researcher or entrepreneur. Funding may also be acquired or delegated by the program manager. Funding is expected to remain relatively constant for the coming years. There is, however, a strong need for national and international “networking” in order to optimize the rather limited means.

RESEARCH, DEVELOPMENT AND DEMONSTRATION ACTIVITIES

A list of projects benefitting of partial funding by the Swiss Federal Office of Energy is presented in Table 1.

Table 1: Hydrogen Energy Projects and Contractors		
PRODUCTION		
■ Photolysis of water by use of solar energy		University of Berne University of Geneva EPFL Lausanne
■ Chemical cycles based on metal oxides for hydrogen production using concentrated solar energy		Paul Scherrer Institute
■ Electrolysis of water using regenerative energy sources		Various Industries
STORAGE AND TRANSPORTATION		
■ Synthesis and function of new metal hydrides		University of Geneva
■ Hydrogen storage in metals and alloys		University of Fribourg
■ Application of tube and foil membranes		ETH Zürich
■ Seasonal storage of hydrogen in organic hydrides		Paul Scherrer Institute
■ Storage and transport of hydrogen in Quasi-Liquid-Metal-Hydrides		IS Burgdorf
■ Fast filling and gaseous hydrogen		I. Cyphelly, Les Brenets PanGas, Winterthur
UTILIZATION		
■ Hydrogen engine		LARAG Vehicles, Wil
■ Hydrogenation of CO ₂ to alcohols and further chemical commodities		ETH Zürich
■ Reduction of metal ores and other novel processes		University of Hamburg
SUPPORTING ACTIVITIES		

■ Materials science and process engineering for hydrogen technology	Paul-Scherrer-Institute University of Hamburg
■ Advanced education for hydrogen technology and systems analysis, organization of national and international symposia and conferences	Various Institutions

SIGNIFICANT ACHIEVEMENTS

Hydrogen Production

Promising results have been achieved in the field of photolytic water cleavage into hydrogen and oxygen. It has been found very recently by Prof. G. Calzaferri and his team (University of Berne) that oxygen can be liberated by irradiating a silver chloride/zeolite system with visible light. The major breakthrough is certainly the recycling step of the formed silver, i.e. the reoxidation of nanoscopic metallic silver to the "initial" silver cation, i.e. the reversible redox cycle. The teams of Prof. M. Grätzel (EPFL Lausanne) and Prof. J. Augustynski (University of Geneva) developed and optimized a tandem photoelectrode system consisting of a dye-sensitized titania electrode coupled to a platinum electrode, where hydrogen can be produced. As alternative system to the mentioned silver chloride/zeolite system, nanostructured, transparent tungsten oxide acts as an efficient photoelectrode for the production of oxygen. In summary, three processes can be performed:

- The solar driven cleavage of water into hydrogen and oxygen;
- The solar driven cleavage of seawater into hydrogen and chlorine;
- The photoelectrocatalytic oxidation of organic pollutants into hydrogen and carbon dioxide.

It could be demonstrated that the tandem cell cleaves water and/or seawater with an efficiency of greater than 4.5%.

At the Paul Scherrer Institute progress has been achieved in two different pathways for hydrogen generation:

- Kinetics and mechanisms of the two-step cycle for the solar thermal cleavage of water using redox processes of iron oxides has been characterized in detail. There are, however, severe engineering and reactor problems for the thermal reduction at 2200K. The water splitting process, i.e. the production of hydrogen by the reaction of FeO (wüstite) and water, has been successfully demonstrated.
- The reaction of zinc oxide with methane has been investigated. Zinc metal and synthesis gas or hydrogen can be obtained with high yields. Recent results show that zinc oxide also undergoes thermal reduction (this system is considered as promising complement to the iron oxide system).

During the last few years the technical feasibility of high pressure electrolysis systems has been tested. At present the results are being evaluated and in the coming spring the future research and development activities will be decided upon. There are perspectives to locate an electrolyser center including peripheral technologies in the southern part of Switzerland.

Storage Technologies

The search for technically suitable and cheap metal hydrides has been pursued by two research teams at the Universities of Geneva and Fribourg. Many new attractive metal hydrides have been synthesized

and characterized with respect to composition, crystallographic structure, hydrogen storage capability and charge/discharge cycles.

At the IS Burgdorf Quasi-Liquid-Metal-Hydrides (metal hydride microparticles) are suspended in an inert fluid with high heat conductivity, allowing for advantageous storage of hydrogen as a "liquid fuel". The kinetics of charging (hydrogenation) and discharging (dehydrogenation) require further optimization. In a first phase, using a small test reactor, 2-2.5 kW thermal outputs were achieved. A scaled-up project is scheduled to start in 1997.

The technology of storing hydrogen in liquid organic commodities, the methylcyclohexane toluene-cycle, has been further optimized. Together with the electricity industry, the feasibility of this technology for the seasonal storage of energy in these organic hydrides shall be demonstrated with a small pilot reactor.

During the past five years various processes for the dehydrogenation of organic liquids were investigated. The development of appropriate tube and foil membranes for an improved performance of the catalytic reactors and increased hydrogen yields was emphasized. These activities are crucial for the implementation of highly efficient hydrogen charging/discharging cycles in related storage systems.

Utilization of Hydrogen

The catalytic reduction of carbon dioxide to alcohols and further commodities is studied at the ETH Zürich. Major successes have been achieved for the catalytic synthesis of methanol and amines. Some of the catalyst systems have been patented.

Apart from "classical" applications of hydrogen as an energy carrier for fuel cells or for engines, or chemical commodity for industrial reduction processes of organic compounds, some efforts have been spent at the University of Hamburg to identify and characterize processes relevant for the mining industry where hydrogen could replace carbon. This approach not only leads to a mitigation of carbon dioxide emissions but also gives rise for new mining and metallurgy technologies.

Supporting Activities

The results of the Swiss Hydrogen Energy research and development program are published in internationally renowned journals and in the National Energy Information Service (ENET), as well as presented at international congresses. An Annual Report describing the programs and summarizing the supported projects is issued by the Federal Office of Energy. Selected reports are submitted to the IEA International Energy Technology Data Exchange System (ETDE) as well. Within the IEA research and development programs, some of the subtasks are coordinated by Swiss representatives (Subtask A, Annex 10. Subtask A. Annex 11 and SolarPACES Task II: Solar Chemistry).

The organization of international meetings and congresses is supported. The *International Symposium on Metal Hydrogen Systems*, Les Diablerets (August 25-30, 1996), or the *International Symposium on Solar Chemistry*, Paul Scherrer Institute, Würenlingen (October 6-8, 1997) may be mentioned.

The dissemination of knowledge, feasibility and experience on hydrogen technologies is promoted by courses at educational and industrial institutions.

COMMERCIAL ACTIVITIES

Industries like Hrand Djevahirdjian SA, Monthey (production of sapphire and other precious stones,

large scale hydrogen production by a high pressure electrolyser), Pangas AG, Winterthur (hydrogen trader), Linde Dryotech AG, Luzern (liquefaction of hydrogen) and Leclanché SA, Yverdon are all concerned with hydrogen technology. Owing to economical reasons, however, the implementation of novel processes or the enhanced large-scale applications of hydrogen as a fuel is still very problematic.

OUTLOOK

The successful promotion of hydrogen energy and technology depends not only on the research and development progress, but also on the transfer of the results into technical and industrial applications. Therefore, efforts to identify new application niches, novel processes or products based on hydrogen technology will be intensified. Simultaneously, the fundamentals of hydrogen energy and technology will be perpetuated in order to enlarge the basic knowledge, but also in order to open the spectrum of potential applications.

Hydrogen technology is believed to be a crucial "corner pillar" of a future global sustainable energy system. Thus, the international research and development activities gain more importance with respect to the coordination and implementation of joint projects. Owing to the economical disadvantages and the ecological advantages, progress will depend on improving the knowhow and on finding small- and mid-scale applications. This task affords enhanced investigations in hydrogen materials science and hydrogen process engineering.

UNITED STATES

Hydrogen Energy Activities in the United States

Neil Rossmeissl, U.S. Department of Energy

NATIONAL POLICY

The U.S. Department of Energy (DOE) has considered the potential use of hydrogen as an energy carrier since the early 1970s, following the OPEC oil embargo.

During the 1980's, steady advances were made in energy efficiency and renewable energy technologies, and the potential for hydrogen as an energy carrier and fuel linked to renewable energy sources became increasingly apparent. This was further strengthened by the passage of the Spark M. Matsunaga Hydrogen Research, Development, and Demonstration Act of 1990 (P.L. 101-566). The act directed DOE to accelerate efforts to develop a domestic capability for producing and using hydrogen energy to reduce dependence on fossil fuels, engage in technology transfer, and link hydrogen production to the development of renewable energy resources.

Under the directive of the Matsunaga Act, the DOE formed the Hydrogen Technical Advisory Panel (HTAP) in 1990 to facilitate the development of hydrogen as an energy carrier. The Panel acts as an advisory board to the DOE Program management, and is composed of representatives from industry, universities, financial institutions, and environmental organizations. The Panel developed the following vision statement:

Hydrogen will join electricity in the 21st century as the primary energy carriers in the nation's sustainable energy future. Both energy carriers will ultimately come from renewable energy sources, although fossil fuels will provide a long-term transitional resource. Future hydrogen suppliers will deliver a significant portion of America's energy for transportation and other applications. For these applications, hydrogen offers a non-polluting, inexhaustible, efficient, and potentially cost-effective energy system derived entirely from domestic energy sources.

In response to the Matsunaga Act and the follow-on Hydrogen Future Act of 1996 (P.L. 104-271), DOE has reevaluated the mission and objectives of its Hydrogen Program. The Program has developed new transitional and long-range goals and strategies, focused on balancing risk among its core research and development projects, and planned for significant cost-shared technology validation and demonstration projects for its advanced technologies. All of these program elements are designed to move hydrogen into the U.S. energy economy as rapidly as is technologically and economically feasible.

PROGRAM STRUCTURE

DOE recognizes the need to establish the hydrogen option as an important part of a long-term national energy strategy. The Hydrogen Program's mission is to encourage and support the development of safe, practical, and economically competitive hydrogen technologies and systems to meet transitional and large-scale energy needs.

Through its Hydrogen Program, DOE provides national leadership in the developing these technologies. DOE recognizes that long-term development of hydrogen technologies is beyond the resources of a single company or industry, and development requires contributions from several disparate technical

disciplines that reside in many different organizations.

The Program acts as a catalyst in the research and development of hydrogen technologies, by working in partnership with industry to create new business opportunities. The Program also initiates cost-shared joint demonstrations with industry and other research and development sectors.

Management of the Hydrogen Program is the primary responsibility of the DOE Program Management Team, who set the overall technical direction, establishes milestones, and monitors progress of activities. The Team relies extensively on input from the HTAP and the National Hydrogen Association (NHA). The NHA is the key avenue for industry input.

The Hydrogen Program is organizationally within the Office of Solar Thermal, Biomass Power, and Hydrogen Technologies which is part of DOE's Office of Utilities Technologies within the Office of Energy Efficiency and Renewable Energy. To ensure that funds are allocated to a portfolio of technologies with balanced risk and potential for achieving near-, intermediate-, or long-term success, the Program involves three areas: Research and Development; Technology Validation; and Analysis. Activities are carried out at national laboratories, universities, and industrial research laboratories. The Hydrogen Program management team relies on an extensive and exhaustive peer review process to insure the highest quality research is conducted.

FUNDING

U.S. Department of Energy funding for the Hydrogen Program is shown below:

Year	Amount
1991	\$ 2,500,000
1992	\$ 1,400,000
1993	\$ 3,850,000
1994	\$10,000,000
1995	\$10,000,000
1996	\$14,500,000
1997	\$15,000,000

RESEARCH AND DEVELOPMENT (R&D)

The Program's research and development (R&D) projects are directed toward the basic "building blocks" of a hydrogen economy: production, separation and storage, transport, and utilization. Core research and development consists of concept development around specific critical technologies, followed by component development. The Program leverages its resources through coordination with other federal research programs, and emphasizes research on critical technological barriers to the economic feasibility of hydrogen energy. The process is dynamic, and individual research and development activities evolve from the results of, and questions raised by, ongoing projects.

Hydrogen Production

Production research is focused on identifying and improving technologies that have significant potential for overcoming cost and energy source barriers. There are active R&D projects for photoconversion methods such as photobiological and photoelectrochemical systems, and thermochemical processes such as gasification and pyrolysis. These technologies are in the early research and development stages, but have significant potential for being cost-effective and environmentally beneficial production

systems. The goal of this research is to achieve a solar conversion efficiency of greater than 10% for photoprocesses, a catalyst lifetime of 10+ years for thermal processes, and a production cost comparable to current hydrogen production costs (\$5 to \$15 per gigajoule).

The following projects were funded by the Program in Fiscal Year 1997 to further advance hydrogen production technologies; performing organization is given in parenthesis:

Biological Systems

- Algal Production (National Renewable Energy Laboratory)
- Photosynthetic Water Splitting (Oak Ridge National Laboratory)
- Microbes and Bioreactors (National Renewable Energy Laboratory)
- Sustainable Bioreactor System (University of Hawaii)

Electrochemical Systems

- Photocatalytic Cleavage of Water (University of Oklahoma)
- Photoelectrochemical Production (University of Hawaii)
- Direct Water-Splitting (National Renewable Energy Laboratory)
- Dual Bed Photosystem (Florida Solar Energy Center)

Thermal Systems

- Biomass-to-Hydrogen (National Renewable Energy Laboratory)
- Gasification of Biomass and Wastes (Lawrence Livermore National Laboratory)
- Supercritical Water/Biomass Gasification (University of Hawaii)
- Sorption Enhanced Reaction Process (Air Products)
- Plasma Reforming (Massachusetts Institute of Technology)

Hydrogen Separation and Storage

Cost-effective separation and storage systems are critical to the widespread use of hydrogen as a viable energy option. Improved separation technologies can significantly impact the cost-effectiveness of many processes. Current storage methods are too expensive and do not meet the performance requirements of the various applications. This is especially true for hydrogen's potential use as a transportation fuel, where there is a need for high energy density — energy content in a given volume — and lightweight mobile storage. At ambient temperature and pressure conditions, hydrogen has an extremely low energy density, about 1/3300 that of gasoline. DOE's long-range storage goal for transportation is to achieve weight and volume storage densities comparable to gasoline.

Volume density and weight are not such critical factors for utility and other stationary applications; rather, storage efficiency — maximum recoverable energy from the storage process — and system costs are the major considerations. The Program's storage efficiency goal is 75% and system costs should add no more than 50% over hydrogen production costs to the overall cost, or about \$3 to \$5 per gigajoule.

An economic, practical hydrogen storage system depends on capacity, structural integrity of the storage material, total cost, and conditions required for storage, including temperature, pressure, and purity of hydrogen. Research into future storage technologies focuses on physical storage in a compressed gas or liquefied state, solid-state storage using gas-on-solid adsorption in materials such as high surface area carbon, or absorption in the interstices of a metal hydride.

The following projects are funded by the Program in Fiscal Year 1997 to further advance hydrogen separation and storage technologies; performing organization is given in parenthesis:

Separation Systems

- Separation Membrane Development (Savannah River Technology Center)
- High Temperature Membranes (Florida Solar Energy Center)
- Controlled Permeation through Glass (Praxair)

Storage Systems

- Carbon Nanotubes (National Renewable Energy Laboratory)
- Microspheres (Lawrence Livermore National Laboratory)
- Metal Hydrides (Energy Conversion Devices)
- Stationary Storage (A.D. Little)
- Hydride Development (Sandia National Laboratory)
- Polyhydride Complexes (University of Hawaii)
- Fullerenes (Oak Ridge National Laboratory)

Hydrogen Utilization

Many uses of hydrogen are long-term in nature and will depend on technological advancements in the areas of production, storage, and transportation. The most near-term application is expected to be in transportation, either as a fuel additive, as fuel for IC engines, or for fuel cell/electric vehicles. Current research is focusing on near-term applications that will be part of the transition from a fossil-fuel economy to a hydrogen-based energy economy.

The Program is addressing safety and certification issues of hydrogen use. A common perception is that hydrogen is a dangerous fuel, while, in fact, it is not any more hazardous than other fuels currently in common use. The Program is evaluating system safety as a technological risk factor.

The goal of hydrogen utilization research is realization of efficiency and environmental benefits in the energy marketplace. The Program seeks to reduce current levels of end-use emissions by 50% and increase end-user energy efficiency by 20% over 1993 values. In nearly every end-use application, hydrogen has the potential to be more efficient in energy conversion than fossil fuels, and less harmful to the environment.

The following projects are funded by the Program in Fiscal Year 1997 to further advance hydrogen use and safety technologies; performing organization is given in parenthesis:

Utilization

- Polymer Electrolyte Fuel Cells (Los Alamos National Laboratory)
- Regenerative Fuel Cells (Lawrence Livermore National Laboratory)
- 200 kW Hydrogen-fueled Power Plant (International Fuel Cells)
- Lean Premixed Burners (Sandia National Laboratory)
- ICE and Vehicle Systems (Sandia National Laboratory, Lawrence Livermore National Laboratory, and Los Alamos National Laboratory)
- Hydrogen Blended Fuels for Vehicles (NRG)
- HBr Reversible Fuel Cell (SRT)

Safety

- Low Cost Hydrogen Sensors (Oak Ridge National Laboratory)
- Fiber Optic Sensors (National Renewable Energy Laboratory)
- Hydrogen Safety Studies (University of Miami)

TECHNOLOGY VALIDATION

One of the primary goals of the DOE Hydrogen Program is to ensure that partnerships with industry members help to develop and deploy safe, environmentally friendly, cost-effective hydrogen energy systems

for transportation, heating and cooling, electricity generation, and other appropriate energy and fuel uses. The program also seeks to assist U.S. businesses in becoming more competitive in the global economy by providing clean industrial technologies, enabling industry to be less energy- and resource-intensive, and eliminating or reducing the need for environmental cleanup and remediation.

The Program focuses on achieving the technological advances that will enable hydrogen to become an economically viable part of the national energy resource mix.

Validation Projects

Pre-commercial technologies for niche market applications have the potential for near-term economic and technological viability and will be key targets for demonstration projects, such as hydrogen production by electrolysis for storage and end-use by electric utilities using low-cost, off-peak power or intermittent renewable power sources, such as photovoltaic and wind installations. The following projects are funded by the Program in Fiscal Year 1997 to validate hydrogen technologies; performing organization is given in parenthesis:

- Palm Desert Transport System (Schatz Energy Research Center)
- Clean Corridor ICE Vehicle Test (TDM)
- Defense Conversion (Lawrence Livermore National Laboratory)

Integrated Systems - Phase I Solicitation

In Fiscal Year 1996, the U.S. Department of Energy (DOE) issued a solicitation to encourage private-sector participation in the DOE Hydrogen Program. The overall goal of the DOE Hydrogen Feasibility Studies - Phase I Solicitation is to assist industry in the development and validation of integrated hydrogen energy systems and enabling technologies. The objective of the feasibility study is to enable the applicant and DOE to evaluate the potential for near-term implementation of hydrogen technologies or to evaluate the potential for long-term development of integrated hydrogen energy systems or technologies.

As a result of the Solicitation, a total of nine projects have been selected for final eligibility determination and negotiations of awards from DOE. The selected organizations and summaries of their proposed projects are given below:

Bruderly Engineering Associates, Florida

This project will build upon the well-developed infrastructure for the production and distribution of liquid hydrogen in Florida, given the presence of Kennedy Space Center. The project will evaluate the creation of hydrogen energy systems to satisfy emerging demand for clean vehicles and energy systems in niche commercial, agricultural, and military applications.

Energy Conversion Devices, Michigan

This project will develop technical and business plans for the manufacture and commercialization of Integrated Photovoltaic Electrolysis-Metal Hydride Hydrogen Generation and Storage Systems. The project will bring hydrogen-related technologies to the marketplace with minimal component development, but with significant emphasis on proper integration of the component technologies. Several near-term market applications, including 'niche' markets, have been identified.

General Atomics, California

This project will evaluate the development of a low cost, environmentally attractive method for the production of hydrogen from biomass fuels. General Atomics will perform a feasibility study for the application of supercritical water gasification to the economical production and end-use of hydrogen from renewable biomass energy sources.

International Fuel Cells (IFC), Connecticut

This project will evaluate the development, validation, and commercialization of an integrated hydrogen generator system. The system incorporates an advanced compact fuel processor and an advanced hydrogen upgrader system to purify the hydrogen to customer requirements. The new IFC technology for the processing of carbonaceous fuels is expected to operate at high efficiencies and reduced capital cost relative to state-of-the-art reforming.

International Fuel Cells (IFC), Connecticut

This project consists of a feasibility study to define a hydrogen-fueled portable electric generator to compete with mid- to large-size batteries and small- to mid-size internal combustion engines. A polymeric electrolyte membrane (PEM) fuel cell will be used as the energy converter and the fuel will be stored in a hydride which will be an integral part of the generator.

M-C Power Corporation, Illinois

This project will evaluate the production of electricity from biomass through hydrogen, using a molten carbonate fuel cell (MCFC). This system will include a biomass gasifier, a gas purification train, and a fuel cell for electric power generation. The ultimate product is intended to be a biomass-fueled MCFC power plant in the 1- to 5-MW size range.

Southeastern Technology Center, Georgia

This project will perform a feasibility study to determine the technical characteristics and commercial attractiveness of small industrial vehicles employing a fuel cell power system with onboard hydrogen storage.

Teledyne Brown Engineering Systems, Maryland

This project will study the feasibility of small PEM fuel cell power sources for existing and future markets, with emphasis on fuel cells in the high-value niche market of small, remote power sources. The project is intended to lead to the manufacture and selling of packaged fuel cell systems in the 0.1 to 0.5 kW range.

The Electrolyser Corporation, New York

This project will evaluate two hydrogen fueling systems. The first is a Fuel Cell Electric Bus filling station, which would use utility Integrated Electrolysis to produce hydrogen. The second system is a home garage filling station or Hydrogen Vehicle Refueling Appliance which would incorporate a small hydrogen generator, compressor, and fuel dispenser and would be designed to "time-fill" a vehicle overnight.

ANALYSIS

Analysis is conducted in parallel with R&D and validation activities and is used to measure technological progress and to evaluate potential markets for hydrogen. These studies include analyses of technologies and processes and the definition of infrastructure requirements for hydrogen major market sectors. Results provide guidance to ensure that investment in research and development and technology validation is directed to those systems and technologies with the best possibility of being implemented, and demonstration candidates that have the greatest opportunity for market success.

Any new energy source or carrier should be evaluated in the context of costs and benefits for industry and society at large. The Program has established a Systems Analysis Team to conduct an integrated analysis agenda that will help create a balanced portfolio of R&D and validation projects. This portfolio will be defined with industry and other key members of the hydrogen community to reduce risk and increase the successful implementation of hydrogen technologies. Tasks conducted under the analysis agenda will define performance and cost targets and critical R&D needed to reach these targets.

The Hydrogen Program is focused on the needs of the marketplace. The Program works closely with industry, industry associations, and consumers to assess how the use of hydrogen can be expanded in the marketplace. The assessments include interactions with the utility, chemical, natural gas, petroleum, alternative fuels, and transportation industries; trade and professional associations; and insurers.

RECENT ACCOMPLISHMENTS

The U.S. DOE Hydrogen Program reported a number of significant accomplishments in Fiscal Year 1996:

Production

- Identified CO₂ sorbent that exceeded project goals of capacity, kinetics, and cycling (Air Products)
- Demonstrated continuous operation of bacterial water-gas shift reaction system in excess of 12 months with no degradation in system performance (National Renewable Energy Laboratory)
- Demonstrated a solar-to-hydrogen conversion efficiency of 7.8% under natural sunlight with no measurable degradation (University of Hawaii)

Storage

- Determined hydrogen storage density of 10 wt% on a nanotube basis at 285K, and that storage capacity is significantly increased by purposeful oxidation of nanotube caps (National Renewable Energy Laboratory)
- Identified a Mg-rare earth phase that improves release kinetics and is more stable than Mg-Ni (Sandia National Laboratory)

Utilization

- Achieved performance stability in 2,000-hour test of fuel cell (Los Alamos National Laboratory)
- Developed improved predictive capability for NO_x emissions (Lawrence Livermore National Laboratory)
- Developed a new fiber optic sensor design that is more sensitive, with a detection time constant of 0.2 seconds and a recovery time constant of 1 second (National Renewable Energy Laboratory)

Technology Validation

- Built, tested and delivered a prototype Personal Utility Vehicle (Schatz Energy Research Center)
- Designed, built, and delivered a portable refueling station and a fuel cell test station (Schatz Energy Research Center)

Analysis

- Determined economic feasibility of various renewable hydrogen production technologies (National Renewable Energy Laboratory and Energetics, Inc.)
- Evaluated economic parameters for fuel cell vehicles and infrastructure requirements (Directed Technologies, Inc. and Princeton University)

OUTLOOK

The Hydrogen Program's strategy is a combination of near- and long-term actions to support hydrogen's development as a principal energy carrier. The Program is promoting research and development that will position hydrogen as an affordable, acceptable, safe, and practical option in the energy marketplace.

This strategy emphasizes using validation and demonstration of hydrogen technologies to identify commercial opportunities in niche and near- and mid-term energy markets. Niche markets, such as California's Zero Emission Vehicle requirements, and near-term demonstrations are initial steps toward the longer term hydrogen economy. This approach is critical, because the transition to hydrogen as a primary carrier is a long-term problem requiring the development of technologies with long lead times and the investment of substantial capital resources.

Since the passage of the Matsunaga Act and now with the Hydrogen Future Act, there has been a significant change in the Hydrogen Program. The Program will gradually introduce hydrogen as a component in a transition energy economy. This transition will move the United States from the fossil fuel based economy of today to the hydrogen based economy of tomorrow.

This transition economy is being aided by the emergence of natural gas as the nation's primary fossil fuel of choice. Hydrogen can be blended with natural gas to reduce

emissions and, in the case of transportation, to improve engine performance. The natural gas delivery and storage systems may ultimately provide an infrastructure for widespread hydrogen use, if adequate technological advances are made.

The Hydrogen Program is a long-term research and development effort, and while there is the potential for some near-term applications, any significant integration into the energy economy will require decades of technology improvement and testing. Even with this long time frame, the transfer of hydrogen technology into the private sector must take place incrementally.

Since hydrogen's potential as an energy carrier emerged during the energy crisis of the 1970's, the vision of a hydrogen-based energy economy has seemed to out pace the realities of hydrogen energy technology. The DOE Hydrogen Program is putting projects in place that will help the vision become reality during the next several decades. Substantial advancements are required in technologies for hydrogen production, storage, transport, and utilization before this future can be achieved.

TASK 10 - PHOTOPRODUCTION OF HYDROGEN

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Task Description

The objective of the Task is to investigate and develop processes and equipment for the production of hydrogen by direct conversion of solar energy. These processes should have the potential to be efficient, economically competitive and environmentally benign. Photoelectrochemical and photobiological processes are studied in this Task, which is divided into the following subtasks:

■ Subtask A: Photoelectrochemical Hydrogen Production.

This includes two main activities:

- C Development of innovative concepts for water splitting (involving evolution of hydrogen and oxygen).
- C Evaluation of non-oxygen-evolving systems, emphasizing the potential of combining hydrogen production with waste degradation.

■ Subtask B: Photobiological Hydrogen Production

This involves the metabolic production of hydrogen by micro-organisms (algae or bacteria) using light as an energy source. The subtask includes the following activities:

- C Screening and characterization of hydrogen producing micro-organisms, establishing an Internet data bank based on information from literature and available culture collections.
- C Genetic studies of such micro-organisms aimed at increasing their hydrogen producing capacities.
- C Development of photobioreactors, feasibility studies and cost estimates of photobiological hydrogen production.

■ Subtask C: Standardization of Methods for Measurement, Calculation and Reporting of Efficiencies.

This subtask was finished and reported during 1996. (J.R. Bolton: "Solar Photoproduction of Hydrogen", IEA/H2/ TR-96).

■ Duration

Task 10 started on 1 March 1995 and will continue through February 1998.

Participation

In 1996 Task 10 had the following participants: Italy, Japan, Norway, Sweden, Switzerland, the United Kingdom and the United States.

Activities and Progress During 1996

Two experts meetings were held, one in Stuttgart, Germany on 27-28 June and one in Tokyo, Japan on 17-18 October. The June meeting was arranged in conjunction with the 11th World Hydrogen Energy Conference (WHEC), which was held in Stuttgart 23-28 June 1996. This led to good attendance at our meeting, since many experts attended the 11th WHEC. Several German experts were invited as observers on the first day, and there was an interesting exchange of information.

The Programme of Work was reviewed and revised at the Stuttgart meeting. Four activities were defined for Subtask A (responsible expert in parentheses):

- C Electrochemical characterization of semiconductor/water interface (SiC/H₂O) (John Turner)
- C Conductive and/or catalytic transparent films (Rick Rocheleau).
- C Oxygen or chlorine evolution by photoelectrochemical process (Jan Augustynski).
- C Semiconductor devices for water splitting and water depollution (Clovis Linkous).

For Subtask B, the following three activities were defined:

- C Preparation of an Internet data bank on hydrogen-producing micro-organisms (Yasuo Asada).
- C Genetics of cyanobacteria and other microbes useful in photobiological hydrogen production (Peter Lindblad)
- C Photo-bioreactor development and process cost analyses (John Benemann).

The attendance at the Tokyo meeting in October was rather poor, due to the fact that many experts (notably those from the USA) did not obtain funding for attendance. Those present reported on the progress made, these contributions are collected in a "Proceedings". The Programme of Work was again reviewed, and some revisions of milestones etc., were made. The workshop was followed by a one-day excursion to Tsukuba, visiting three of the national laboratories there. In conclusion the Tokyo meeting turned out to be fruitful and constructive in spite of the poor attendance.

Subtask A

The following institutions participated in Subtask A: National Renewable Energy Laboratory (NREL), Hawaii Natural Energy Institute (HNEI), Florida Solar Energy Center (FSEC) - all in the United States; Geneva University, Bern University, Federal Polytechnic School of Lausanne - all in Switzerland; National Institute of Resources and Environment (NIRE), Japan; and University of Uppsala, Sweden.

At NREL (like other US institutes) hydrogen work was somewhat cutback in 1996, due to lack of funding during the summer. Dr. John Turner participated, however, in both Annex 10 meetings. He reported on progress with GaInP₂/GaAs tandem cells for water splitting, achieving hydrogen and oxygen production with 8-12% efficiencies. He has also started development of a relatively large scale demonstration photoelectrochemical reactor for water splitting.

Dr. Rick Rocheleau from HNEI presented some results at the Stuttgart meeting. He is working on direct photoelectrolysis of water using multi-junction amorphous silicon-based photoelectrodes with appropriate catalytic surfaces. The efficiency obtained so far is 7-7.5% on an active surface of 0.27 cm² and was stable for 144 hours in an outdoor efficiency test. A proposal for joint research between NREL, HNEI and the University of Geneva was formulated. This research will involve the growing and characterization of various compositions and structures of amorphous silicon carbide films. Due to a lack of funding, the project could not start in 1996.

Dr. C. Linkous from the FSEC is attempting to realize the direct photolytic conversion of water into H_2 and O_2 via a dual bed process, where photocatalysts and reaction conditions are chosen respectively to reduce or oxidize water. The photocatalyst currently under study for the O_2 evolution mode is TiO_2 . However, the high band gap (3 eV) drastically limits the attainable efficiency. Thus, the Geneva experience on WO_3 with a band gap of 2.6 eV might represent an important advantage. High surface area, highly photoactive WO_3 , will be prepared according to the procedure supplied by Dr. Augustynski. The results will be compared with those obtained from TiO_2 slurries.

Prof S.E. Lindquist of Uppsala, who joined Subtask A in 1996, is a member of the Consortium of Artificial Photosynthesis in Sweden. The programme involves approximately 20 researchers and is granted by Knut and Alice Wallenberg's Foundation. His in-depth broad knowledge is of very high value for the subtask.

Dr. Arakawa from NIMC in Japan has shown that, whilst $NaCO_3$ is promoting the photocatalytic water splitting in TiO_2 suspensions, it works only in the UV part of the spectrum. Therefore, this approach cannot constitute an alternative to the other lines under investigation. Dr. Ibusuki, NIRE, Japan is developing thin film catalysts with special emphasis on the determination of the surface properties. Collaboration is foreseen with Dr. Linkous.

In Switzerland, a joint project aiming at splitting water by a tandem cell made out of one photoelectrode in TiO_2 , activated by an organic dye coupled with a second photoelectrode in WO_3 , is under way. Three groups participate in this research: the University of Geneva (Prof I. Augustynski), the Federal Polytechnic School of Lausanne (Prof. M. Gratzel) and the University of Bern (Prof. G. Calzaferri). Prof. Augustynski represented the whole team at both the Stuttgart and Tokyo workshops. 1996 has been a year of significant progress. Transparent WO_3 layers have been deposited on various substrates with good reproducible characteristics. Tandem cells were realized with an active surface of 1.5 cm^2 . The blue part of the spectrum is absorbed in the WO_3 at the surface of which the O_2 is produced, whilst the remaining part of the spectrum reaches the TiO_2 where protons are reduced to H_2 . The efficiency is now approximately 4.3% for the splitting of pure water into H_2 and O_2 and 4.8% for the splitting of sea water into H_2 and Cl_2 . In Bern Prof. Calzaferri was able to show the feasibility of reoxidizing the silver reduced by the photooxidation of water to O_2 . This important result constitutes a prerequisite for the possible use of Ag loaded zeolites as an alternative to WO_3 .

The addition to the progress made in the individual research centers participating in Subtask A, progress resulting from collaboration must be mentioned. Prof. Augustynski from Geneva has given to C. Linkous a description of his method of producing good quality WO_3 to be used instead of TiO_2 in his slurry photolysis concept.

Dr. J. Turner from NREL sent multi-junctions of amorphous silicon to Prof. Augustynski in order to investigate the possibility of WO_3 being deposited on them. This would promote the evolution of oxygen at the anode and thus prevent undue corrosion of the silicon. Unfortunately it does not work, since the thermal treatment necessary to obtain acceptable WO_3 layers is harmful to the semi-conductor device. An alternative concept is being developed in Geneva to overcome this difficulty. It combines the good performance of the multijunction and the WO_3 efficiency, and protects the semi-conductor device from the electrolyte contact, thus avoiding the risk of pinholes. The first results are very encouraging.

In conclusion, it can be stated that important progress has resulted from the 1996 activities in spite of the financial shortage of many of the groups participating in Subtask A. Efficiencies ranging from 4.5% (Swiss group) to 7% at HNEL and up to 12% at NREL have been obtained.

Much progress remains to be made in order to reach a level where an industrial development can be considered. In the dual TiO_2 - WO_3 concept, the efficiency has to be increased to 6-7% (1997) and

should be further raised to 10% (1998-99). This aim is ambitious, but not unrealistic. For the amorphous silicon multi-junctions, the efficiency obtained is already good. It is probable that it can be increased further. However, the problem of efficient protection against oxygen corrosion requires much attention, and the solution must enable the development of fairly large pinhole-free cell surfaces. The collaboration with the Geneva group may help in making progress towards this goal. The very high efficiency reached at NREL is impressive. For a large scale application, the cost of large surface, efficient III-V devices appears today as a considerable obstacle, however, the possibility of either finding a satisfactory solution to this problem, or developing specific applications where the high cost is acceptable, cannot be excluded.

Subtask B

The following institutions participated in Subtask B: National Institute of Biology and Human Technology (NIBH), Japan; Hawaii Natural Energy Institute (HNEI), National Renewable Energy Laboratory (NREL) and Oak Ridge National Laboratory (ORNL), U.S.; Kings College London, UK; Norwegian Institute for Water Research (NIVA), Norway and Uppsala University, Sweden.

Screening and characterization of hydrogen producing micro-organisms are ongoing activities in several laboratories. Initiatives were taken by Subtask B participants to coordinate these activities and organize data from relevant micro-organisms in a databank. At the 8th International Congress of Culture Collections (ICCC-8) in the Netherlands in August 96, Olav Skulberg (NIVA) presented a request for collaboration and data compilation. Thus, the large European and world-wide culture collection organizations (ECCO and WFCC) are getting engaged. Data from existing representative culture collections at NIVA and HNEI will contribute substantially to the databank. Dr. Asada (NIBH) has compiled a list of literature data. A problem with such data is that they are not very consistent. Methods for measuring hydrogen production capacities have not been standardized, and differ with respect to light sources, units of light intensity, basis for hydrogen evolution, etc. Therefore, compilation and presentation of the data on a consistent manner is not straight-forward.

During the screening and investigations carried out at NIVA, an interesting observation was made. A strain of cyanobacteria named *Aphanizomenon gracile* showed a high frequency of heterocyst formation and a correspondingly high performance of hydrogen evolution.

Research at Oak Ridge National Laboratory on hydrogen and oxygen production by microalgal water splitting continues to make progress. It has been shown that certain mutants of the green alga *Chlamydomonas reinhardtii* are capable of sustained simultaneous photo-evolution of molecular hydrogen and oxygen as well as reduction of atmospheric carbon dioxide. The most recent progress in this area was published in the July 19, 1996 issue of *Science*, where it was demonstrated that certain Photosystem I-deficient mutants of *Chlamydomonas* are capable of photo-autotrophic growth.

The genetics of cyanobacteria and other microbes useful in photobiological hydrogen production are also being studied by several research groups. The group of Dr. Lindblad in Uppsala has been characterizing hydrogenases (enzymes crucial for hydrogen production) in some cyanobacteria including nitrogen-fixing species, *Anabaena* and *Nostoc*. The genes of hydrogenases from the cyanobacteria were identified and compared with some previously known hydrogenase genes. Dr. Lindblad made 5 surveys of collaboration possibilities in the field of genetics, and got a positive response from several research groups. Some topics of interest for collaboration would be:

- C molecular cloning of hydrogenase genes and related studies;
- C physiological and biochemical characterization of hydrogenases;
- C development of genetic engineering systems for hydrogen-producing microorganisms.

Actual co-operative efforts were not initiated in 1996, mainly due to insufficient funding of Subtask B participants. It is hoped that the situation will improve in the coming year.

Photobioreactor development is carried out by most of the research groups participating in Subtask B. At NIVA an experimental photobioreactor of alveolar type (Fig. 2) was constructed and operated. It has a high surface to volume ratio and is used for various algal studies, including photobiological hydrogen production.

A collaborative effort was initiated between the University of Florence (Prof. M. Tredici) and HNEI (Dr. O. Zaborsky) on the development of an internal gas exchange tubular photobioreactor for cyanobacterial hydrogen production. Based on the design concept of Prof. Tredici, a demonstration unit will be built and operated at HNEI in Honolulu. Other Subtask B participants will be connected for inputs, information and participation in this activity.

A first draft of a feasibility study (Process analysis and economics of biophotolysis) was prepared by Dr. J.R. Benemann. It contains a preliminary design and cost estimate of a plant with an output of 10 million SCF/day (280,000 Sm³/day) of hydrogen. The design is based on a two-stage indirect biophotolysis process, where algae are grown and induced to fix CO₂ in one reactor, and then transferred to a different reactor for the photoproduction of hydrogen. An advantage of this concept is that the first step can be carried out in large open ponds, which are relatively cheap to construct. The algal suspension is concentrated before transfer to the hydrogen-producing stage. Thus, the more expensive equipment required in this stage may be of relatively small volume. Another advantage is that hydrogen and oxygen evolution take place separately. Also, the CO₂ evolved in the second stage can be re-used in the first one. This is, of course, only one of many possible configurations, but one that can be relatively easily costed since many of the costs are known from similar plants.

The preliminary cost estimates yield a unit cost of approximately 11 USD/MMBTU (~10 USD/GJ) of hydrogen. This is roughly twice the cost of hydrogen from natural gas with current technology and prices, but about half the cost of hydrogen by water electrolysis with current electricity prices. Obviously, this is still in the conceptual stage, and much R&D remains to be done, both on the genetic adaptation of microorganisms to hydrogen production, and the development of cheap and efficient reactors.

Activities Planned for 1997

The spring experts meeting will be held at the Paul Scherrer Institute in Switzerland on 16-18 April. On this occasion, a meeting will be held with Annex 10 experts and some experts from Task II (Solar chemistry) of the SolarPACES programme. There are areas of common interest in these programs, and possibilities for cooperation will be discussed.

The fall meeting will be held in October at NREL, Colorado. Another important event in 1997 is the BioHydrogen '97 conference, taking place on 23-26 June in Hawaii. Annex 10 will be a cosponsor of this event, and will participate actively. A special Subtask B meeting will be arranged in connection with the conference.

Subtask A activities:

The Swiss group will continue to develop their special tandem concept and apply it to the splitting of water and brine (sea water), as well as degradation of organic pollutants combined with hydrogen evolution. Development of thicker transparent layers of WO₃ is expected to give enhanced efficiencies. Alternative dyes will be tested on the dye-sensitized TiO₂ electrode to permit its use as a "blue window"

to be superimposed on the WO₃ electrode.

Cooperation between Swiss and US experts will continue. More samples will be exchanged for characterization and for attempts to combine WO₃ and a-Si-electrodes. At NREL work will proceed on the design of a photoelectrochemical demonstrator reactor. In Japan, Dr. Sayama at NIMC, Tsukuba will follow up the activities of Dr. Arakawa. Dr. Ibusuki at NIRE will continue his participation. Cooperation with US experts is foreseen.

Subtask B activities:

Screening of hydrogen producing micro-organisms and collection of data will continue. The data bank will probably be established on the Internet during the summer. Cooperative projects in genetics will be established. The construction and operation of a photobioreactor at HNEL will proceed in cooperation with Prof. Tredici at the University of Florence. Based on operating experience, more refined design studies and cost estimates will be carried out.

Meeting Schedule for 1997

16-19 April 1997 Meeting in Villigen, Switzerland

June 1997 Subtask B meeting in Kona, Hawaii in connection with BioHydrogen '97

October 1997 Meeting at NREL, Golden, USA

Publications

James R. Bolton: "Solar photoproduction of hydrogen". IEA Technical Report, IEA(H2/TR-96, September 1996.

Task 10: Photoproduction of Hydrogen. Proceedings from Experts Meeting in Tokyo, 17 October 1997. (Internal report).

Y. Asada: "Photobiological hydrogen production. State of the art with special reference to IEAs Hydrogen Programme". Hydrogen Energy Progress XI (Proc. of 11th WHEC), Vol. 1, pp.403-406.

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M. Grätzel: "Photocatalytic and electrocatalytic properties of mesoscopic oxide semiconductor films". Contribution to the 4. Ulmer Electrochemische Tage, Ulm, Germany, July 1996.

G. Calzaferri: "Artificial antenna systems". Solar Energy Materials, 1997 (In press.),

TASK 11 - INTEGRATED SYSTEMS

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Task Description

The objective of this effort is to develop a tool to assist in the design and evaluation of potential hydrogen demonstration projects and in the optimization of existing hydrogen demonstration projects. Emphasis will be placed on integrated systems covering all components, from input energy to end use. The activities will be focused on near- and middle-term applications, with consideration of the transition to sustainable hydrogen energy systems.

Systems under consideration include stand-alone and grid-connected hydrogen production and hydrogenation systems; hydrogen and oxygen transport and storage systems; conversion devices including fuel cells, turbines, combustors, and hydrogenation units; electric load leveling systems; and general characteristics of mobile applications.

The task participants will undertake research within the framework of three highly coordinated subtasks. This work will be carried out in cooperation with other IEA Implementing Agreements, where appropriate.

■ Subtask A: Case Studies

Hydrogen energy systems will be critically evaluated and compared, with system performance measurement as the central focus. Safety and regulatory issues will be considered where appropriate.

The data base of demonstration projects will be updated and extended to include new projects and additional data according to requirements of Subtasks B and C. A case study report will be produced.

■ Subtask B: Analysis Tools

Subtask B will focus on simulation activities that build on existing modeling efforts. Using data collected in Subtask A, these component models will be validated. If necessary, additional data will be requested from Subtask A, to complete validation.

The component models will then be adapted into the integrating platform, and parametric studies will be conducted to identify promising strategies for improving the performance of selected components. A report describing the models will be produced and the component models will be organized into a library that will be made available to the participating countries.

■ Subtask C: Design Guidelines

Guidelines will be developed to assist in the design of future demonstration plants to meet operating and user requirements, and to facilitate the systematic integration of hydrogen into the energy system.

System models will be built in the integrating platform, based on individual component models developed in Subtask B. Base case validation and optimization runs will be conducted and the results compared to data collected in Subtask A. Requests will be made for additional project data (Subtask A) and component models (Subtask B).

A report will be prepared that includes recommendations for the optimization of existing hydrogen systems and design guidelines for new, promising, and desirable hydrogen systems.

■ **Duration**

The Task was formally begun on August 1, 1995 and will continue until July 31, 1998.

■ **Expected Results**

The collaborative efforts of Task 11 will result in the following outputs:

- C Case study report to document the selected hydrogen energy systems;
- C Report describing the component models, including the required inputs and the expected outputs, and limitations and capabilities of the models;
- C Library of component models for use in the common integrating platform; and
- C Report of recommendations for optimizing existing hydrogen energy systems and the set of design guidelines for planning future integrated hydrogen energy systems.

Participation

Seven countries are participating in Task 11: Canada (Subtasks A and B); Italy (Subtasks A and C); Japan (Subtasks A, B, and C); the Netherlands (Subtasks B and C); Spain (Subtasks A and C); Switzerland (Subtasks A and B); and the United States (Subtasks A, B, and C).

The Lead Countries for Subtasks A, B, and C are Switzerland, the United States, and the Netherlands, respectively.

Activities and Progress during 1996

Activities during 1996 were focused on continuation of data collection, the initiation of model development and validation, and the initiation of system integration.

At the World Hydrogen Energy Conference in Stuttgart, Germany (June 24-27, 1996), the poster paper *Methodology Development for Analysis of Integrated Systems* was presented. The poster consisted of a short description of this IEA activity, with photographs and diagrams of the hydrogen demonstration facilities from around the world that are part of this effort.

A number of notable contacts were made during the poster presentation. Dennis Bevington, the mayor of Fort Smith, Northwest Territories, Canada, discussed the possibility of providing information on the remote power/hydrogen demonstration underway in his city. Christine Parra, from the Schatz Energy Research Center, discussed the progress of the integrated demonstration project being developed in Palm Desert, California. Stefan Schlagowski, from the Solar-Wasserstoff-Bayern project, discussed the project in Neunburg vorm Wald (the site of the Spring 1997 Experts Meeting).

In the wrap-up session that followed the poster session, the discussion focused on process integration issues, which is the primary focus of this IEA effort. Numerous requests for additional information and copies of the poster were received and processed.

The Subtask Leaders and the Operating Agent met in Stuttgart, Germany on June 25, 1996 to discuss progress and to initiate the development of the Technology Teams. Dr. Thomas H. Schucan (Paul Scherrer Institut, Switzerland), Mr. Hajo Ribberink (ECN, Netherlands), and Mr. Joseph Badin (Energetics, Inc., USA) met with the Operating Agent (Ms. Catherine E. Gregoire Padró, NREL, USA) to discuss management issues and technical progress. The concept of Technology Teams was discussed and formalized to assist in the distribution of work effort and to increase participation.

The Fall Experts Meeting was held in Tokyo, Japan on October 28-30, 1996. The Technology Team assignments were formalized according to availability of data, models, or expertise. Team leaders were selected to coordinate the delivery of the completed component models.

Data collection (Subtask A) progressed in a number of areas, although the response from some participants was not adequate. Concerns included collection of detailed data; collection of intermittent system data; and the need for cost parameters. A key issue in the development of survey forms for the collection of detailed data was the identification of requirements. There exists a very close link between the data and the models.

The collection and use of cost information on hydrogen demonstrations raised issues about first-plant costs and the relationship to the costs of future plant generations. Since the projects included in this effort are generally one-of-a-kind plants, the cost data for those facilities are not relevant to future project costs. The potential to link to other Implementing Agreements that are developing future costs (nth plant costs) of renewable systems was discussed. Subtask A Leader will serve as the focal point for these interactions.

Component model development (Subtask B) progressed. Models for the production of hydrogen from biomass gasification, biomass pyrolysis, and coal gasification were completed. Transport models for high pressure hydrogen pipelines and distribution pipelines were also completed. Development continued on additional models including four types of fuel cells, hydride storage, chemical storage, compressed storage, and gas turbines.

The Baseline Application Requirements (Subtask C) was completed, pending final review. The list of existing and potential hydrogen energy systems to be investigated was finalized.

Personnel changes that occurred in 1996 include the assignment of Mr. Maarten Bracht of ECN to represent the Netherlands, and to serve as Subtask C Leader in place of Mr. Hajo Ribberink, who has accepted other duties at ECN. In addition, Mr. Joseph Badin of Energetics has accepted new challenges and Dr. Edward Skolnik, also of Energetics, has been selected to represent the USA as Subtask B Leader. We thank Mr. Ribberink and Mr. Badin for their conscientious efforts over the past 18 months, and welcome the participation of Mr. Bracht and Dr. Skolnik.

Work Planned for 1997

Collection and analysis of information will continue in all subtasks. The work is following the schedule developed in 1995, with a small modification to the schedule to correct the inconsistency between the schedule for Subtask B component model availability and the integration of these models in Subtask C.

The Spring Experts Meeting is scheduled for April 10-11, 1997 in Neunburg vorm Wald, Germany. The meeting is expected to be attended by experts in process design, hydrogen systems, and analysis. Discussion will focus on the development of the component models, and the integration of these component models into hydrogen systems, using the integrating platform.

The Fall Experts Meeting, to be held in Italy or Canada, will focus on the optimization of the integrated

models and the initiation of the development of the design guidelines.

Scheduled activities for 1997 by subtask are:

Subtask A:

- C Develop detailed questionnaire on environmental, safety, and acceptability aspects of hydrogen technologies
- C Coordinate detailed information and data needs between Technology Teams
- C Update data base

Subtask B:

- C Perform parametric studies and optimization runs on component models
- C Develop component models and adapt to integrating platform
- C Request additional data as required

Subtask C:

- C Request additional project data and component models
- C Build integrated system models
- C Perform validation runs
- C Begin development of design guidelines

Meeting Schedule for 1997 and 1998

April 10-11, 1997	Germany
Fall, 1997	Italy or Canada
Spring, 1998	Switzerland
July, 1998	TBD - Final Meeting

TASK 12 - HYDROGEN STORAGE IN METAL HYDRIDES

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Task Description

Metal hydrides offer a “solid” alternative to the storage of hydrogen in gaseous and liquid form for vehicle fuel. They are volume efficient, inherently safe, require only uninsulated low pressure containers and do not involve cryogenic technology. However, hydrides are heavy in comparison to the hydrogen they carry. The purpose of this Task is to develop hydrides for on-board storage that have a combination of improved gravimetric capacity and lower temperature release of hydrogen. In addition, the option of reversible electrochemical hydrogen storage is included.

The specific targets of the Task are as follows:

- C The identification of a formulation technique for a metal hydride material that is capable of 5 wt.% hydrogen capacity with a dehydriding temperature of less than 150 °C.
- C The development of a metal hydride surface treatment such that high-efficiency, reversible electrochemical reactions can be accomplished over thousands of cycles.

The Task is highly experimental in nature and is centered around four methodology-related Subtasks:

- **Subtask A: Synthesis Techniques**, where unusual materials are made by non-conventional techniques.
- **Subtask B: Characterization of New Materials and Surfaces**, where properties are evaluated relative to the above targets.
- **Subtask C: Evaluation of Manufacturing Technology**, where practical large-scale production and costs of promising materials will be analyzed.
- **Subtask D: Applications Analysis**, where vehicular and other potential applications will be analyzed relative to the hydriding properties of the newly developed materials.

Project Descriptions

During 1996, a materials-related project structure was developed in parallel to the methodology- related structure outlined above. Seven distinct projects were established. The first six are experimental in nature and are accompanied by Hydride Material Development Plans (HMDP). Each project is led by one of the Task 12 Experts and involves international contributions by other Experts. Brief descriptions of the projects follow:

- **Project 1: Destabilized magnesium nickel hydride** [Leader: D. Noreus (Sweden); co-participant: USA]

The classic A_2B hydride Mg_2NiH_4 is usually formed above 240°C and forms a micro-twinned structure

upon cooling. This hydride is too stable and requires undesirably high temperatures for H₂ desorption. It is believed that the synthesis of Mg₂NiH₄ below 240°C will result in a twin-free microstructure and a destabilization effect manifested in a decreased desorption temperature. The object of this project is to experimentally test this theory.

- **Project 2: Vapor phase synthesized Mg₂Ni** [Leader: G. Thomas (USA); co-participants: Norway, Sweden, Switzerland]

Unusually pure, single phase Mg₂Ni can be made by the reaction of Ni powder with Mg vapor. This material exhibits higher H₂ desorption kinetics and slightly higher plateau pressures. This project is concentrating on (1) characterizing the micro-structure of vapor-synthesized Mg₂Ni and (2) attempting to further increase the desorption H₂ pressure by high-energy processing of the powder.

- **Project 3: Fine-structured RE(Mn,Al)₂ alloys** [Leader: L. Schlapbach (Switzerland); co-participants: Japan, Norway, Sweden, USA]

RE(Mn,Al)₂ alloys (RE=rare earth elements) offer the possibility of low-cost, high capacity hydriding alloys. However, alloys made by conventional melting do not show distinct advantages over the prior art. This project is attempting to improve the hydriding properties by introducing fine (nanocrystalline) microstructures using unconventional techniques, particularly high-energy ball milling and rapid solidification.

- **Project 4: Laves phase CaAl₂-X_b alloys with substitutional and interstitial elements X** [Leader: I. Uehara (Japan); co-participants: Sweden, Switzerland]

The AB₂ Laves phase CaAl₂ offers the possibility of high hydrogen storage capacity with extraordinarily low materials cost, at least in principal. Unfortunately, CaAl₂ has anomalously low H-capacity. The purpose of this project is to attempt to correct this problem by the partial replacement of Al by other elements.

- **Project 5: Preparation and characterization of titanium-aluminum alloys as potential catalysts for reversible alkali metal - aluminum hydrides** [Leader: A. Maeland (Norway); co-participants: USA, Germany (subject to approval)]

Bogdanovic (Germany) has recently shown that the normally nonreversible complex hydrides of Na and Al can be made reversible by the incorporation of Ti catalysts. The purpose of this project is to test the theory that it is really the in situ formation of Ti-Al compounds (e.g., Ti₃Al, TiAl, etc.) that are responsible for the catalytic activity.

- **Project 6: Structural investigations of intermediates and end products in the synthesis of Ti-doped alkali metal - aluminum hydrides** [Leader (tentative): B. Bogdanovic (Germany); co-participants: Japan, Norway, Sweden, USA]

Ti-doping renders the normally nonreversible NaAlH₄ and Na₃AlH₆ hydrides reversible (see also Project 5). Although the kinetics are low, along with possible cyclic stability problems, Ti-catalyzed alkali metal - aluminum hydrides are close to meeting the capacity-temperature target of Task 12. This project aims at developing a clear understanding of the chemistry of the system so that reasonable judgments can be made toward the design of improved catalysts. The project leader is listed as tentative because Germany has not yet joined Task 12.

- **Project 7: Comprehensive Hydride Review and Associated IEA Databases** [Leader: G. Sandrock (USA)]

This project is aimed at cataloging past work on hydriding materials and applications in support of IEA Task 12 and its search for new and innovative hydriding materials. It is also aimed at encouraging hydride R&D throughout the world by making past results widely and easily accessible via the Internet in the form of on-line IEA databases. The databases can be reached at the Sandia National Laboratories' Hydrogen Information Center (<http://hydpark.ca.sandia.gov>).

■ Duration

Task 12 was officially initiated September, 1995, for a duration of three years.

Participation

The countries that participated during 1996 are Japan, Norway, Sweden, Switzerland and the USA. It is anticipated that Canada and Germany will join in 1997.

Activities and Progress during 1996

Experimental activities for Task 12 had a slow start. Project plans 1-6 were developed during the first eight months of 1996 and experimental work started on Projects 1-5 about September, 1996. The first round of compositions have been synthesized for these five projects with experimental evaluations and special processing runs started. For Project 1, preliminary results are positive, indicating that low temperature, twin-free Mg_2NiH_4 is somewhat destabilized relative to the high-temperature, twinned form, i.e., the H_2 is desorbed at 20-30 C lower temperatures. For Projects 2-5, sufficient results are not yet available to judge as to success or failure. Project 6, as planned for leadership by Bogdanovic, requires the official participation of Germany in Task 12. Approval for German participation was not received by the end of 1996.

Project 7 (Comprehensive Hydride Review) was started October, 1995, and proceeded with good progress through most of 1996. A 34-alloy Hydride Properties Database was constructed and opened on the Sandia Web Site in December, 1995. Its availability was announced via a news release in January, 1996 and further publicized at the Symposium on Metal-Hydrogen Systems (Switzerland) during August, 1996. A survey of on-line use during May-September, 1996, averaged about 10 international users per day, more than expected for such a specialized database. A Hydride Organizations Database was started on-line in December, 1996, with 14 individual organization profiles submitted for the initial release. A large Hydride Listing Database was fixed for release late in December, 1996, and is expected to be on-line during January, 1997. It contains 1260 listings in the alloy categories A_2B , AB, AB_2 , AB_5 , misc. inter-metallic compounds and solid solutions. In addition, a linked and searchable Reference Database (637 entries) was fixed in December and will go on-line during January, 1997.

Work Planned for 1997

Projects 1-5 will continue as planned. The HMDPs are scheduled for first round completion and reporting during July, 1997. At this time, second round extensions will be planned for those projects showing promising results. Projects with negative results will likely be terminated and new ones substituted. Project 6 will be started early in 1997, hopefully with the support of Germany. If Germany elects not to participate, the project will proceed with leadership from another participating country.

Two other experimental project proposals are expected early in 1997. One will be led by a likely new member, Canada, and involve nanocrystalline materials made by mechanical alloying. The other project will be proposed by Switzerland and Germany and will involve high-pressure gaseous synthesis

of new metal hydrides.

Project 7 will continue with the expansion of the Reference Database and new hydride listings in the categories Mg alloys, Multiphase Alloys & Composites, Amorphous & Nanocrystalline Alloys and Other Special Alloys. In addition the Hydride Properties Database will be expanded beyond the present 34 records. A Hydride Applications review will also be started. The databases will be compiled in hardcopy form and published as an IEA Technical Report.

Publications and Presentations

G. Sandrock, G. Thomas and J. Schwegel: "IEA/DOE/SNL Hydride Properties Database", Dec. 1995, Sandia National Laboratories Hydrogen Information Center, World Wide Web Site <http://hydpark.ca.sandia.gov>.

G. Sandrock, G. Thomas and J. Schwegel: "On-Line Hydride Database", Poster Paper, International Symposium on Metal Hydrogen Systems, Les Diablerets, Switzerland, Aug. 28, 1996.

G. Sandrock and G. Thomas: "IEA/DOE/SNL On-line Hydride Databases", U.S. Department of Energy Hydrogen Technical Advisory Panel Meeting, Englewood, CO, Oct. 16, 1996.

G. Thomas, T. Pope and G. Sandrock: "Metal-Hydrogen Organizations Database", Dec. 1996, Sandia National Laboratories Hydrogen Information Center, World Wide Web Site <http://hydpark.ca.sandia.gov>.

Meetings Held in 1996

Experts' coordination meeting and technical workshop, Les Diablerets, Switzerland, Aug. 27, 1996 (in conjunction with the International Symposium on Metal Hydrogen Systems)

Meeting Schedule for 1997

11-13 March 1997: Alexandria, VA, U.S. (in conjunction with the National Hydrogen Association Annual Meeting)

13-18 July 1997: Henniker, NH, U.S. (in conjunction with the Gordon Research Conference on Hydrogen-Metal Systems)

Publications and Presentations Planned for 1997

G. Sandrock, G. Thomas and T. Pope: "IEA/DOE/SNL Hydride Materials Listing and Reference Databases", Jan. 1997, Sandia National Laboratories Hydrogen Information Center, World Wide Web Site <http://hydpark.ca.sandia.gov>.

G. Sandrock and G. Thomas: "Compilation of IEA/DOE/SNL Hydride Databases", IEA Technical Report, mid-1997.

G. Sandrock and G. Thomas: "IEA/DOE/SNL Hydride Databases", Poster Paper at Gordon Research Conference on Hydrogen-Metal Systems, Henniker, NH, July 13-18, 1997.

Additional IEA Technical Reports and Technical Papers as warranted by results of individual IEA 12 projects.

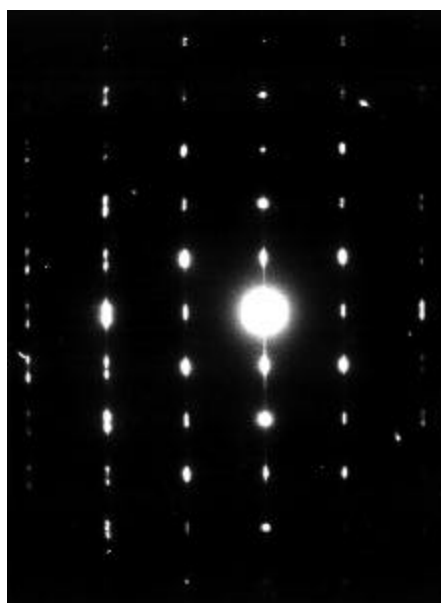
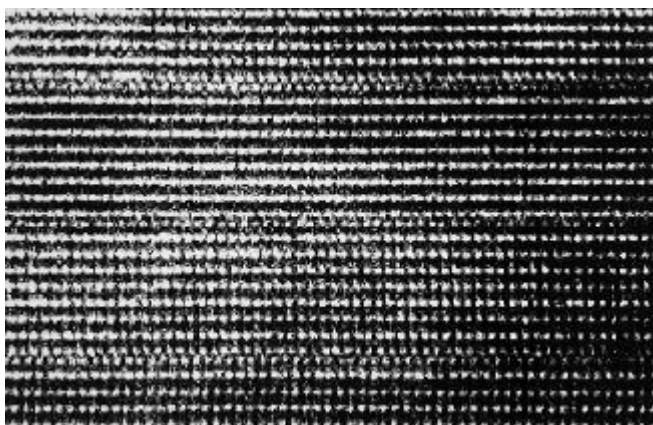


Figure - High-resolution, transmission electron micrograph (top) and electron diffraction pattern (bottom) of monoclinic Mg_2NiH_4 formed above 240°C and cooled to room temperature (Noréus, Sweden). The TEM photograph shows horizontal rows of Ni atoms, with each row about 0.66 nm apart. When Mg_2NiH_4 is cooled below 240°C , stacking faults develop, three of which can be seen in the “zipper-like” features in the TEM photo. These faults separate crystal blocks that have microtwinned relationships to each other as can be demonstrated from the fragmentation and streaking seen on the electron diffraction pattern. The microtwins result in a stabilization of the hydride, i.e., make it harder to liberate H_2 gas. The microtwins can be avoided by forming the Mg_2NiH_4 below 240°C and the resultant twin-free, low-temperature structure will liberate its H_2 more easily than the microtwinned, high-temperature structure.